CLOSING LOOPS IN SUPPLY CHAIN MANAGEMENT:

DESIGNING REVERSE SUPPLY CHAINS FOR END-OF-LIFE VEHICLES

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Proefschrift

ter verkrijging van de graad van doctor aan de Universiteit van Tilburg,
op gezag van de rector magnificus, prof. dr. F.A. van der Duyn Schouten,
in het openbaar te verdedigen ten overstaan van een door het college voor promoties
aangewezen commissie in de aula van de Universiteit op

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door

Henricus Maria le Blanc

geboren op 12 april 1979 te Veghel, Nederland.

Promotor:	Prof. dr. ir. H.A. Fleuren
Co-promotor:	Dr. ir. H.R. Krikke

For Maaike

and my parents

Preface

"Vrije tijd is de tijd die er over blijft wanneer men zijn werk gedaan heeft en waarmee men geen raad weet, als je begrijpt wat ik bedoel."
Olivier B. Bommel (5310)

This thesis is the result of four years of hard work. I learned a lot in these years, it is an enrichment of my life and I hope my work is an inspiration for others and contributes to the body of knowledge. But most of all I hope it will be a practical contribution. Science is good-for-nothing without application today, tomorrow or perhaps the day after tomorrow. In my opinion there is a gap to bridge in applying scientific insights into practice. Fundamental and applied research should not only coexist, they should merge, such that both are lifted to higher level.

The quotations I have added at the beginning of each chapter stem form the Olivier B. Bommel books written by Marten Toonder. Beside entertainment, the stories are a rich source of wise lessons. Even in science we can find the lessons of Toonder. I would like to refer the interested reader to the inauguration speech of professor Heertje (1977) at his appointment as professor in the "Bommeliaanse economie". Since linguistic aspects are of great importance in the work of Marten Toonder, I have chosen not to translate the quotations. I apologize to the foreign readers.

These four years would not have been pleasant without a good working atmosphere. I was lucky to have two circles of colleagues. The staff of CentER Applied Research in Tilburg and the staff of Auto Recycling Nederland in Amsterdam were both good and inspiring surroundings.
Thanks to Auto Recycling Nederland for supporting my research and providing me an interesting practical environment. Special thanks deserve Roelof Reinsma and Annemieke van Burik for listening to and reflecting on my ideas. The outcomes of the projects are promising and the thought that it is being used makes me smile.
Thanks to Harold, my co-promoter, for our endless discussions on reverse logistics and introducing me to the leading researchers in the field. Without your support and your insights the thesis would not have reached this quality.
Thanks to Hein Fleuren, my promoter, for offering me a position as a PhD student in an applied research setting. I learned a lot from you during the projects we did

together, and your support and mild criticism, where necessary, during my PhD trajectory were of great value. Your view on applied (operations) research has motivated me during the last four years and will inspire me in my future career.

Remains to thank my family, it is great to have a group of people to share the good and bad moments with. Thanks to my parents, who made me come this far. They were always willing to help me and stimulated me to develop myself. Thank you for everything. Finally, I would like to thank Maaike. During my PhD trajectory she was always there to support and encourage me and for proofreading all my manuscripts. Most of all, I thank her for all the beautiful moments we shared and will share together in the future.

Ieke le Blanc

Tilburg, August 2005

Contents

Chapter 1

Introduction

"Hoe mooi is het om in deze tijd te leven! Het tijdperk van uitbuiting is ten einde. Er wordt fris en modern aangepakt. Er waait een nieuwe wind. Ik ben reeds jaren doende daar een proefschrift over te schrijven."
Drs. Zielknijper (5443)

This thesis deals with closed-loop supply chain management, in particular for end-of-life automobiles. End-of-life product management, as part of life cycle management, will change in the coming years. Concern for the environment and customers demand for recycling have led to producer responsibility legislation, where also economic factors play a role. The research for this thesis took place in the practical setting of Auto Recycling Nederland, the organization responsible for the recycling of end-of-life vehicles in the Netherlands. This enabled us to develop new theory based on the ongoing developments to supplement the current know-how in the literature. This thesis presents the following:

- An analysis of the logistics concept and operations research modeling approaches for reverse supply chains with a focus on end-of-life returns.
- A set of design principles for reverse supply chain networks that will support practitioners in the (re)design process.
- The application of theory and operations research models in three real-life cases in the logistic network of Auto Recycling Nederland.

This chapter introduces the field of closed-loop supply chains and motivates the goals and setup of the thesis. Section 1.1 defines the field of closed-loop supply chain management. Section 1.2 describes the so-called value perspective, founding the motivation for supply chains to adopt a life cycle approach. The various types of returns found in different stages of the life cycle are classified in Section 1.3. Section 1.4 describes the typical processes in a reverse supply chain. Section 1.5 discusses the motivation for the research and discusses the research questions. The research methodology and the thesis' setup are covered in Section 1.6.

1.1 Defining closed-loop supply chains

Supply chain management has changed relentlessly in the last few decades. Customers have become more and more demanding and demand drives the supply chain. Increased transparency (e.g. through internet sales) has caused a shift in the balance of power towards the customers and gives them the opportunity to actively configure the final product. The focus today is on creating value through personalized and individualized offerings to customers, while at the same time maintaining "traditional" requirements such as high quality and low cost. The market trend towards mass customization has created a variety of product options that a company must offer. Businesses that are expanding into international markets must be able to manage manufacturing and distribution on a global basis. Cross-company concepts, referred to as supply chain management, are necessary to meet these increasing demands (Krikke et al., 2004).

Supply chain management (SCM) is the integration of key business processes from the end users through the suppliers that provide products, services, and information that add value for customers and other stakeholders (Lambert and Cooper, 2000). Actual realization of SCM occurs by implementing concepts such as efficient consumer response (ECR), continuous replenishment, collaborative planning, vendor managed inventory (VMI) and so on. The application of information and communication technology in the last decade has improved the possibilities for effective supply chain management. Electronic databases, electronic data interchange (EDI), internet protocols, enterprise resource planning (ERP) and advanced planning systems (APS) have become standard applications in supply chain management.

Another fundamental change in the late 20th century is the extension of supply chains into so-called closed-loop supply chains. In a forward supply chain, the customers are typically at the end of the supply chain processes (Guide et al., 2003). Supply chain management is currently experiencing a paradigm shift towards "cradle-to-grave" approaches. The "cradle-to-grave" paradigm is effectuated through life cycle management (LCM). The paradigm shifts may be attributed to various drivers to be discussed later on, but life cycle management always aims at optimizing service, cost and environmental performance of a product over its full life cycle. Key issues include product design for recovery, re-engineering, product data management, installed base support and evaluation of end-of-life scenarios. LCM is supported by methodologies such as life cycle assessment (LCA) and life cycle costing (LCC). Note that “product” also refers to components, packages, carriers, refillable units and so on. As a consequence, the supply chains are extended into closed-loop supply chains (CLSC). The relationship between LCM and CLSC management is reflected in Figure 1.1 (adapted from Westkämper and Van de Osten-Sacken, 1999).

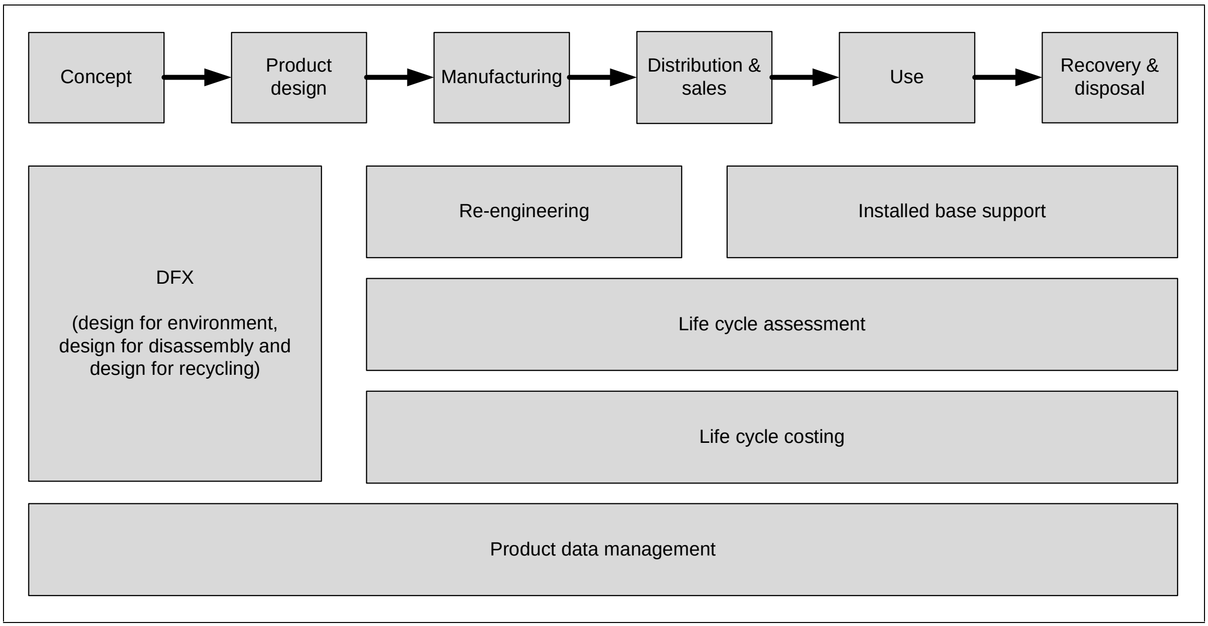

Figure 1.1. Product life cycle management and closed-loop supply chain management (based on Westkämper and Van de Osten-Sacken, 1999).

Closed-loop supply chain management is defined as the integration of business processes that creates additional value for all original and new players in the supply chain through the closure of goods flows from the point of consumption back into a supply chain. Value creation refers to both traditional supply chain objectives, such as customer satisfaction and profitability, as well as environmental goals. In the literature, the terms reverse logistics and reverse supply chains are often used interchangeably, although reverse logistics can be seen as a sub-process in reverse supply chains. For a detailed discussion of the definition of reverse logistics see Rogers and Tibben-Lembke (1998), Fleischmann (2001) and De Brito and Dekker (2004). The closed-loop supply chain covers the combined forward and reverse supply chains. The scope is much broader than the narrow meaning of logistics and considers reversing the good flows from consumers back to the distributors, manufacturers and suppliers.

1.2 Closed-loop supply chains from a value perspective

1.2.1 Closing value loops

Closed-loop supply chains connect the phases of production, consumption and recovery such that a minimum amount of valuable resources is lost (Dyckhoff et al., 2004a). These phases are closely related to value, as shown in Figure 1.2. In the forward supply chain, value is created by extracting resources in the mining or extraction phase, and by producing and distributing products to the consumers. Consumers use the products and extract value during consumption. Servicing or repairing a product during the lifetime is a value-sustaining activity, extending the product's useful life. Despite the value-sustaining activities, the product's life is limited and the product will be discarded. The subsequent recovery processes in the reverse supply chain aim at recapturing some of the value contained in the product and feeding it back into the forward supply chain. Ideally, this loop recovers all the scarce natural resources. Unfortunately, some resources will be wasted and if waste is not properly disposed of, the environmental impact of waste represents a negative externality value. Negative externalities do not only refer to damage to society, but also to direct commercial damage, for example by an affected reputation.

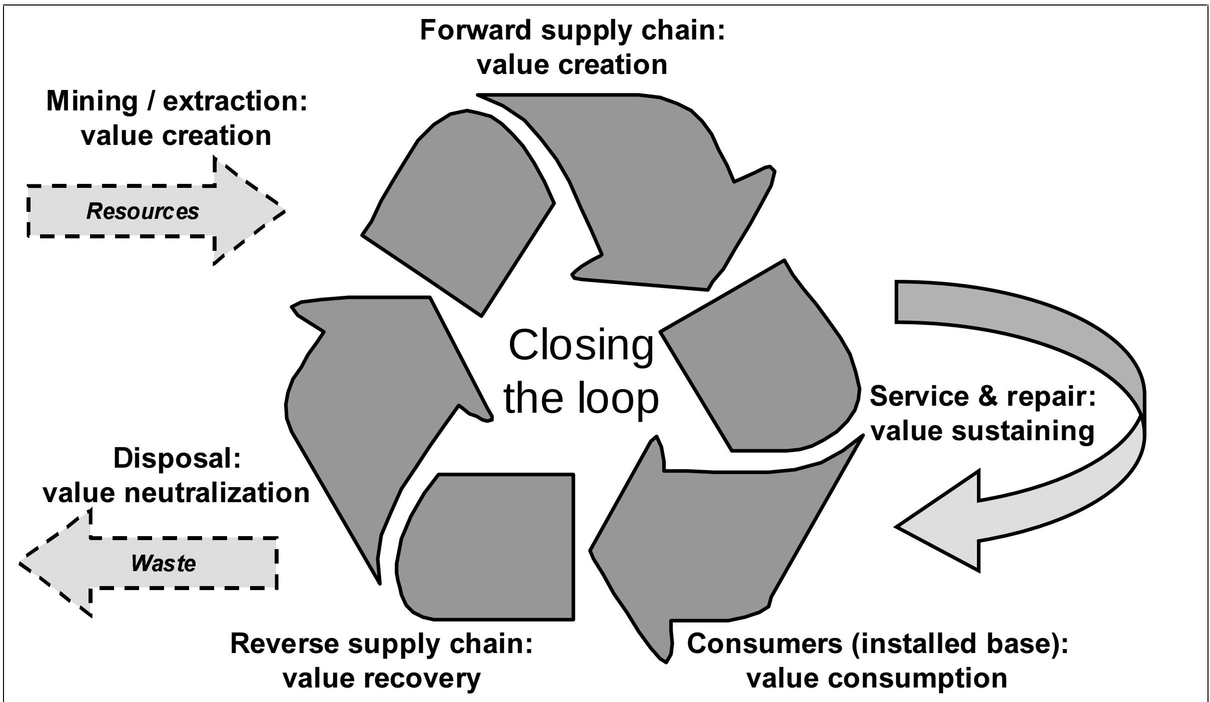

Figure 1.2. Closed-loop supply chains from a value perspective.

Business opportunities should pave the road to the sustainable supply chains. Recovery processes in the simplest form are at least 50 centuries old (Nijkerk and Dalmijn, 1998), but always driven by value opportunities. Worn metal weapons and tools were melted down to make new ones. Structural changes at the end of the twentieth century accelerated the development in not only economic or customer-value recovery, but also the neutralization of negative externalities, as explained in the next section.

1.2.2 Paradigm changes

Section 1.2.1 discussed the value perspective: both the positive economic or customer-value and the negative value because of its environmental impact and potentially related costs. As a result of this value perspective, the focus of supply chains is shifting. The converging system of a series of interrelated processes, directed towards the consumer, is being replaced by a network of processes, aiming at optimization of the entire product life cycle. This shift is caused by several developments related to different types of value:

- Scarcity of resources. Growing awareness of the limited availability of natural resources, such as fossil fuels, will lead to a more careful use of resources. Simultaneously, demand for natural resources is increasing, due to industrial development in Asia, especially China and India. For example, the metal scrap prices more than doubled in 2003 (Minter, 2004). Closing the material loop and recovering natural resources is a logical consequence. A physical product can also be seen as a carrier of resources, such as raw material, labor, machine time, knowledge and energy (see Figure 1.3). Products returned from the market still carry some of these resources. In the recovery phase the remaining value can be recaptured. This paradigm shift is driven by economic value.
- Function selling and servicizing. Function selling or “servicizing” is the process of selling product-based services instead of just a product. In the B2B market for copiers and printers, for example, it is already common to lease a copier or printer for a certain time period, where the customer is charged for the number of prints made. The provider is responsible for the proper functioning and all the necessary maintenance of the machine. Typically, these arrangements allow the provider to change the copier or printer for a machine that better fits customer requirements, for example, when there is a mismatch between the number of indicated prints and the actual number of prints. Similar constructions are also used for vending machines at schools, universities and large companies (Ong et al., 1996). Although this development is still in its infancy in the consumer market, more and more customers appreciate these “flat fee concepts”, in particular for expensive durable products. Optional packages are offered for new cars, allowing the customer to buy out all future maintenance and repairs for a fixed number of kilometers or years. Function selling will contribute to a better environment only if it changes the way in which products are made, used and disposed of (White et al., 1999). By extending involvement of the manufacturer to the use phase,

function selling allows a manufacturer to become the legal owner of a product. This paradigm shift is driven by customer-value.

- Increased product liabilities. The power balance between consumers and manufacturers is shifting more and more towards the consumers. Legislators and consumer right organizations enforce consumer rights, resulting in increased claims and product recalls. The liabilities of manufacturers extend beyond the warranty period; consumers can expect safe and well-functioning products during the whole product life. Competition has increased in several markets, and manufacturers have to invest in service channels to improve customer satisfaction. Product liabilities are not limited to the consumer, but extend to the environment. The basis for many take-back laws in Europe is the policy principle of Extended Producer Responsibility (EPR). EPR is defined as a policy approach in which producers accept significant responsibility, financial and/or physical, for the treatment or disposal of products (OECD, 2001). EPR policies have two characteristic features: the shifting of responsibility upstream to the producer and the provision of incentives for producers to include environmental considerations in the design of their products, resulting in a life cycle approach. This paradigm shift is driven by negative externality value.

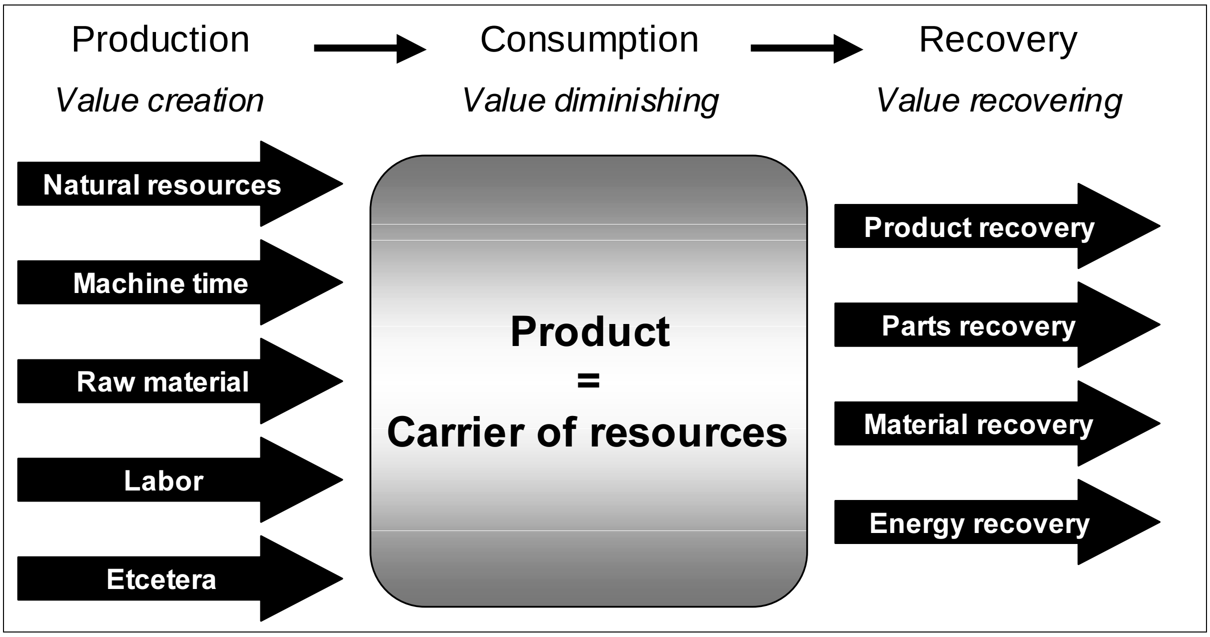

Figure 1.3. The product as a carrier of resources.

1.2.3 Individual drivers

The scarcity of natural resources, the increased product liabilities and the trend towards function selling are long-term developments changing the current business paradigm. Individual supply chains need more specific reasons to extend their chain with a reverse channel to manage the return flows of products. The drivers discussed below are divided into business and legislation drivers, although these two types of drivers are not strictly separated. Legislation sometimes forces industries to undertake appropriate measures, while at the same time business opportunities may occur. For example, legislation protecting consumer rights resulted in warranty and commercial returns, which resulted in a business opportunity to improve customer relationships; some companies offer better service than legally required to distinguish from the competitors.

Supply chains adopting a broad view to product returns discover many business opportunities, this includes:

- Economic gain. Recovery of products and parts can be good alternatives to manufacturing new products and parts, as shown by the examples in the remanufacturing of copier machines (Krikke et al., 1999a) and single-use cameras (Toktay et al., 2000). Recovered materials can be good alternatives to virgin resources, as illustrated by examples in steel recycling (Geyer and Jackson, 2004).
- Marketing. Sustainable development and green marketing have been placed on the strategic agenda of many companies. Most executives acknowledge the importance of social and environmental responsibility to a company's bottom line, its reputation and its customers (Mirvis and Googins, 2004). Consumers boycotted Shell in 1996 since it wanted to dump their drilling rig, the Brent Spar, in the sea. This boycott seriously harmed both Shell's sales and brand value. On the other hand, a green image, or a good reputation regarding corporate citizenship, can even help companies to distinguish themselves from their competitors. This applies not only to the manufacturing industry but also to the service industry. For example, Scandic, a chain of hotels in Northern Europe, adapted a sustainable strategy that resulted in improved customer loyalty, since environmental values are deeply rooted in Scandinavia (Goodman, 2000).
- Better customer relationships. In some sectors, returns are common to preserve or improve the customer relationship. Catalog and internet sellers accept returns as a part of their business; customers would otherwise refrain from placing orders. Customers cannot try on clothing in the catalog or on the internet, so they order different sizes. Even in normal shops, customers have been given the right to return a product a number of days after the purchase. For a discussion of these commercial returns, see Stock et al. (2002) and Blackburn et al. (2004). Should the product malfunction within a certain amount of time after the purchase, the manufacturer is typically required to provide the customer with a replacement or refund of a product. A warranty is a guarantee regarding the reliability of a product, and expresses the manufacturer's confidence in it. The type and

conditions of warranty and the quality of the service channel might differ from manufacturer to manufacturer, but should at least comply with the legal standards. A good service channel for handling defective products, even after the warranty period, is a way for the manufacturer to maintain and extend the customer relationship.

- Market and asset protection. Companies want to protect the brand name (asset) and market. Famous is the example of empty inkjet cartridges collected by third-parties, see Toffel (2004) and Etira (2004). After refilling, the cartridge is sold by the third-party, still referring to the original brand. OEMs typically want to prevent this, in order to protect their brand name and market. Some OEMs even use chips to lock the empty cartridge and a key code is needed for a reset after refilling. Another form of asset protection occurs in the high tech sector, where returns are actively acquired to protect the product from falling into the hands of the competitor, thereby preventing revelation of secret product information.
- Preemption of legislation. Environmental legislation is still absent in some industries, and companies voluntarily take back products to forestall or influence future legislation. Auto Recycling Nederland originated from this idea, as is described in chapter 2. In France, Renault, Peugeot and Citroen also acted in this way in order to prevent direct regulation (Orsato et al., 2002). In Germany, a leading manufacturer of power tools set up a product take-back system in order to demonstrate their commitment in response to drafted legislation (Klausner and Hendrickson, 2000). If self-regulation does not succeed in preventing legislation, it has at least given proactive companies an advantage over the laggards.

Governments use the following legislation to force companies and industries to take back products:

- Legislation protecting consumer rights. Governments have implemented several laws to protect consumers against unfair business practices. In both Europe and the USA, customers have been given the right to return a product within a number of days after the purchase and get a full or partial reimbursement. For catalogue or internet mail orders, the return rates can be as high as 75% (Mostard and Teunter, 2002). Products that do not show the quality or performance the consumer reasonably can expect, given the nature of the goods, can be returned (Directive 1999/44/EC). The manufacturer or the seller of the product has to provide reimbursement, replacement or repair of the returned product. Although companies are obliged to respect the regulations in this area, they can make a virtue out of the necessity by distinguishing their product from competitors and building a better customer relationship.
- Environmental legislation. This type of legislation, which basically enforces product take backs, typically involves the product life cycle phase in which

consumers discard products. Toffel (2003) provides an overview of end-of-life product take-back legislation and mentions three basic goals underlying this type of legislation. The first goal is reduction of the amount of landfilled waste, especially hazardous materials. The second goal involves the increased availability and lower prices of recycled materials in comparison to virgin materials. The third goal is preventing pollution by the reduction of the environmental burden of end-of-life products at the source. Take-back legislation is in force for manufacturers in Europe of packaging, batteries, cars and electrical and electronic equipment. Some countries in Asia and some states in the USA have also adopted take-back legislation for these products. The end-of-life product take-back legislation is typically accompanied by restrictions on the use of hazardous substances (see, for example, Directive 2002/95/EC). With manufacturing on a global basis, which is happening in many industries nowadays, the European legislation is likely to influence products put on the market everywhere in the world.

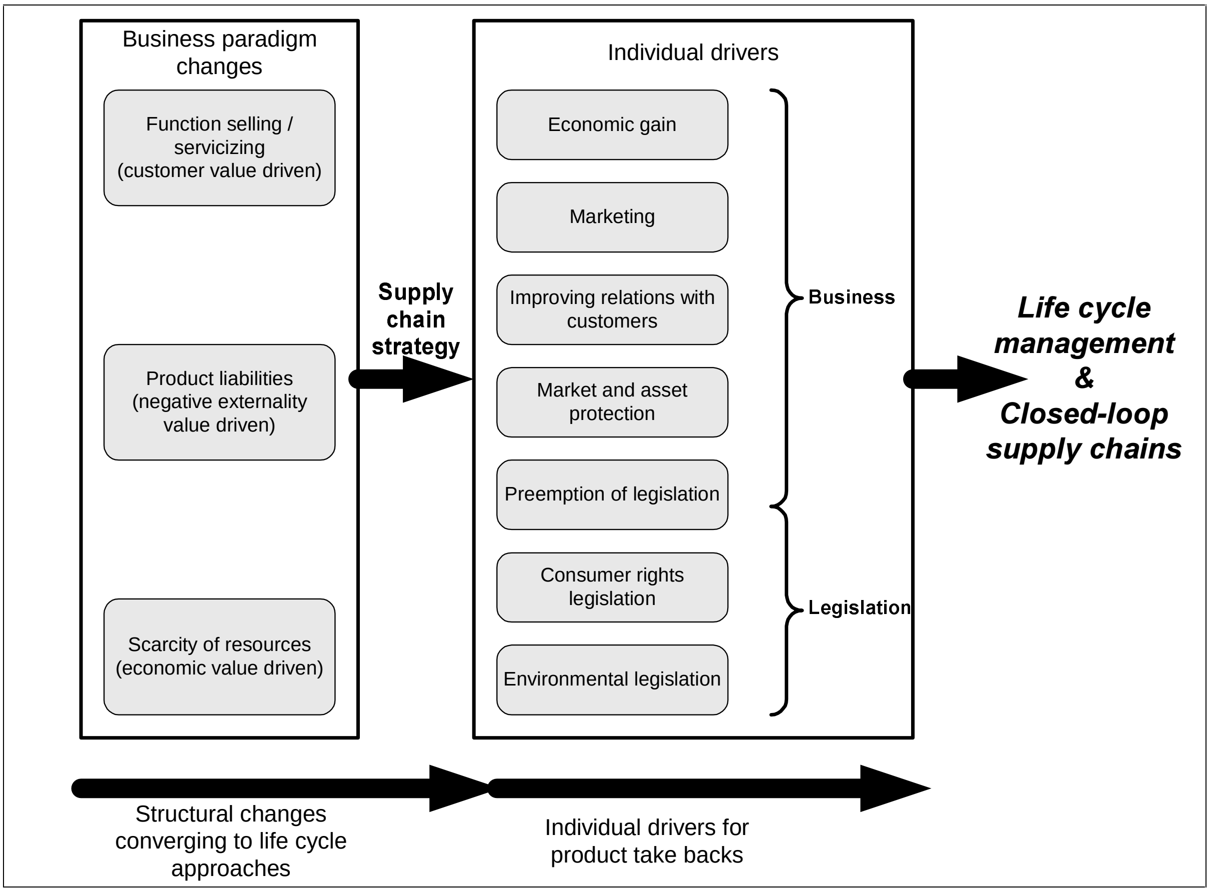

Figure 1.4. Paradigm changes result in individual drivers for managing closed-loop supply chains.

Figure 1.4 shows how the structural changes are translated in individual drivers for supply chains to adopt a life cycle approach, typically as part of the supply chain strategy.

1.3 Types of return flows

The paradigm changes lead to closed-loop supply chains. Closed-loop supply chains extend supply chains by following the product life cycle. Products, components, packages, carriers, refillable units, etcetera, are returned at different points in the product life cycle, resulting in different types of returns, see Fleischmann (2001) and De Brito (2003). Based on the literature, we distinguish six types of returns:

- <u>By-products and scrap</u>. These include materials or products resulting from the production process, that are unavoidable in a blending or cutting process or do not fulfill the quality requirements. Some products can be reworked to meet the quality requirements, while the excess products need to be disposed of or recycled to reduce costs and the environmental impact. Spengler et al. (1997) describe an example in the steel industry where it is technically impossible to avoid a by-product that needs environmentally sound processing because of its contamination with heavy metals.
- <u>Commercial returns</u>. These are product returns that occur during or shortly after the sales process. Among the reasons for commercial returns are customer dissatisfaction, customer tests, overstocking at retailers and promotional actions. For catalogue or internet sellers, accepting returns is critical in establishing and maintaining the customer relationship. Returned products for commercial reasons typically have immediate markets in another location or segment.
- <u>Warranty, repairs and product recalls</u>. These are returns of products or components that are suspected or defect. The customer is entitled to have the same or similar product (function) back. The initiative for returning a product for warranty and repairs lies with the user, while for product recalls the manufacturer actively recalls the products to return. The latter occurs typically with complicated products, where the manufacturer detects potential failures or safety risks the customer is not aware of. Well-known are the examples in the automotive industry. The first versions of the Audi TT, in total about 6,200 cars, were recalled due to bad road-holding ability in high-speed corners. The cars were modified free-of-charge with a firmer suspension, stabilizers and a rear spoiler (Recall Data, 2004).
- <u>Reusable items</u>. These returns are related to consumption, use or distribution of the main product. This type concerns many different items, e.g. reusable containers and pallets, refillable cartridges, bottles, and “one-way” cameras. The

common characteristic is that they are not part of the product itself, but contain and/or carry the actual product. Many examples can be found in society, for example, reusable trays for food in the retirement homes, crates, deposit bottles and containers.

- End-of-use returns. These are products returned after some period of use due to end of lease, trade-in or replacement. Depending on the status of the return, the product is refurbished or repaired and sold through an alternative channel, or remanufactured into new goods. Alternative markets for products can easily be targeted using electronic market places such as eBay, for example. Copier machines that are remanufactured are sold in the same market in another segment, while remanufactured or refurbished cellular phones are sold on geographically different markets.
- End-of-life returns. These are the returns of products that are worn out and no longer useful. Examples are car wrecks, which will be discussed in chapter 2, white and brown goods (De Koster et al., 2005) and carpets (Louwers et al., 1999). The time that elapses before products are at the end-of-life stage is long and quite uncertain, since customers determine when they regard their product as worn out. The products are taken back from the market to avoid negative externalities (environmental or even commercial damage).

1.4 Processes in reverse supply chains

Closed-loop supply chains incorporate the key areas of service logistics, reverse logistics and manufacturing with reuse. This includes both open and closed systems; reuse in alternative supply chains can thus also lead to “closed” goods flows. In this thesis, we focus on the reverse logistics part. The reverse supply chain accompanies typical key business processes. Attempts have been made in the literature to unify these processes, see Nagel and Meyer (1999), Fleischmann et al. (2000) and Guide and Van Wassenhove (2003a). Using the literature, we distinguish the following five key business processes:

- Product acquisition. The retrieval of the product from the market. The timing, quantity, quality and composition of the returned product need to be managed in close cooperation with the chain entities close to the customer. Occasionally, product acquisition happens by active product buy back.
- Collection. These are all the logistic activities in the reverse chain to obtain the products from the market and transport them to the facilities for sorting, disposition, disassembly and finally recovery. This includes processes such as transportation, consolidation, transshipment and storage.

- Sorting, disassembly and disposition. Returned products need to be classified according to quality and composition in order to determine the route in the reverse chain. Market conditions and strategic considerations must be taken into account in the disposition decision. Disassembly often takes place in order to process parts or materials of the original product in different ways.
- Recovery. This is the process of recovering value from the returned product, components and materials.
- Re-distribution and sales. Basically, no value recovery has materialized until the recovered products, components or materials are brought back into a forward supply chain. Re-distribution and sales activities are therefore required.

Depending on the product, the type of return, the quality and position in the product life cycle, one of the several recovery options can be selected. Classifications of product recovery options have been proposed in literature. Thierry et al. (1995) distinguish five recovery options, ordered by the degree of required disassembly of the original product: repair, refurbishing, remanufacturing, cannibalization and recycling. Similarly, one can also refer to the “Ladder of Lansink” (VROM, 2004). The ladder of Lansink denotes five recovery options in theoretical order of environmental consciousness: product re-use, material re-use, incineration with energy recovery, incineration without energy recovery and landfill. Note that landfill and incineration without energy recovery are not considered as ways of value recovery. These types of classifications all rank the options according to assumed environmental desirability; they do not consider, however, the actual environmental effects of the recovery option. More advanced life cycle approaches should be used to assess the true environmental impact and to select the appropriate recovery option. Typically, a combination of recovery options is selected. For example, an end-of-life vehicle can consist of spare parts that can be reused directly; tires then can be retreaded (remanufacturing), while the remaining carcass is shredded for material recycling.
In the remainder of the thesis, we use the following classification of recovery options, which is an extension of Thierry et al. (1995):

- Direct reuse. The product is checked, cleaned if necessary, and sold as it is. This option extends the product life.
- Refill. The carrier or refillable unit is loaded or refilled and can be reused directly.
- Repair. The product is restored to working order by repairing and replacing defective parts.
- Refurbishing. The product is upgraded by replacing the critical parts and components.
- Remanufacturing. A new product is manufactured with the use of the core components of the old product. A remanufactured product is indistinguishable from a newly manufactured product.

- Cannibalization / component reuse. Components from a product are selectively retrieved for reuse, often as spares. A lower grade recovery option is selected for the remainder of the product: recycling, incineration or disposal.
- Recycling. The product is dismantled into several material fractions, for example by shredding and sorting, and the material is reused in new products.
- Incineration. The product is burned to recover energy from the heat generated.
- Disposal. The product or materials are regarded as waste, and sent to landfill sites without any further recovery.

An overview of a closed-loop supply chain indicating the key processes and the recovery options is provided in Figure 1.5.

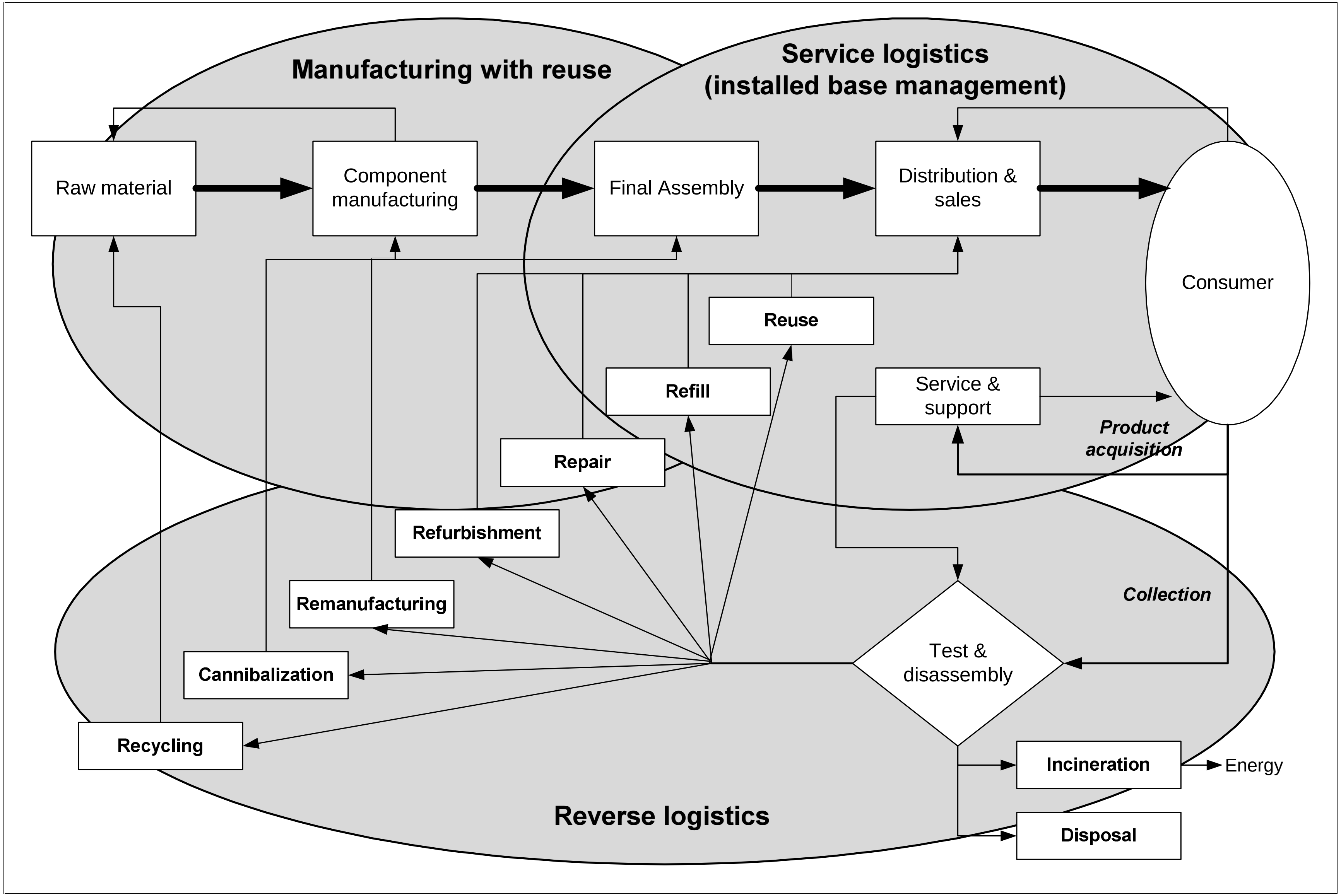

Figure 1.5. Overview closed-loop supply chain.

1.5 Research motivation, goal and questions

1.5.1 Research motivation

Research in the field of closed-loop supply chains has been booming in recent years. The European Commission honored a research proposal on reverse logistics, and in 1997 the RevLog working group was founded, involving six universities across Europe. RevLog aims to analyze the key issues of reverse logistics in five areas: distribution, production planning and inventory control, information technology, business economics and the integration of the reverse logistics issues (RevLog, 2004). In 1998 the Reloop project started aiming at the development of tools for optimization in reverse logistics (Reloop, 2004). Recently, the Dutch government funded a large research and innovation project, Transumo, running from 2004 to 2009 on the transition to sustainable mobility. Within Transumo there is a cluster involved with closed-loop supply chains (Transumo, 2004).

Several Ph.D. dissertations have been written on a number of topics in closed-loop supply chains. Bloemhof-Ruwaard (1996) discusses environmental issues, life cycle analysis and network design. Van der Laan (1997) dealt with inventory management in a remanufacturing environment. Krikke (1998) discussed network design issues and product recovery strategies. Fleischmann (2001) developed quantitative models for network design and inventory systems with product returns. Mayers (2001) investigated the implications for the disposal of electric and electronic equipment. Fergueson (2002) described the development of an information system for automotive recycling. Beullens (2001) focused on network design, process planning and vehicle routing. De Brito (2003) developed a framework and focused on return handling and inventory management.

Closed-loop supply chains have also gained the attention of scientific journals. A number of special issues have recently appeared: Interfaces (Larson et al., 2000), OR Spectrum (Haasis et al., 2001), Production and Operations Management (Corbett and Kleindorfer, 2001a and 2001b), Interfaces (Guide and Van Wassenhove, 2003) and California Management Review (Guide and Van Wassenhove, 2004).

A number of special issues have been announced: Omega (Adenso-Diaz, 2004), Journal of Operations Management (Jayaraman and Linton, 2004), Production and Operations Management (Guide and Van Wassenhove, 2004a) and OR Spectrum (Flapper and Spengler, 2004).

A few books have appeared, that are dedicated to topics in closed-loop supply chains: Rogers and Tibben-Lembke (1998), Guide and Van Wassenhove (2003a), Dekker et al. (2004) and Flapper et al. (2004). In the mainstream supply chain

management literature the topic is also gaining attention: Klose et al. (2002), Dyckhoff et al. (2004) and Fleischmann and Klose (2005).
At international conferences, special sessions have been devoted to the topic of closed-loop supply chains. While some workshops were dedicated to the topic, for example, the closed-loop supply chain workshops held at Duquesne University in 2001, PennState in 2003, INSEAD in 2002 and 2004 and Vanderbilt University in 2005. Other conferences took closed-loop supply chains as one of the major topics, for example, the OR2004 conference held at Tilburg University in 2004.

Despite the rise of research in the field of closed-loop supply chains, the attention for end-of-life returns is relatively limited. Most research focuses on repairable or remanufacturable products. Because, these types of returns are mainly driven by economic motivations, they are of interest in the early research on closed-loop supply chain management. However, scarcity and increasing demand for natural resources makes recycling more and more economically feasible, even for end-of-life returns. Besides the economic stimuli, legislation based on EPR in Europe, the USA and some Asian countries, forces manufacturers to take back worn products from the market. Product liability of the original manufacturer is extended towards the end-of-life phase. Both the environmental awareness of consumers and their expectations that companies act responsible has grown; this has resulted in corporate stewardship. Most successful applications of end-of-life returns have focused on environmental aspects, paying little attention to economic motivations. This research focuses on the economic aspects of end-of-life products, with material recycling as the dominant recovery option. We concentrate on network design aspects and the interaction with other planning processes, in particular routing, since this operational process largely determines the economic efficiency.

The problem definition of this thesis is as follows.

> *For long-term success of end-of-life management, more economic stimuli are needed than is currently the case. Legislation as a single driving force is insufficient for companies to establish reverse supply chains. The key issue is to find eco-efficient solutions, i.e. designing and operating an economically low cost network without violating the targets imposed by environmental legislation. The question is what makes reverse supply chains special compared to forward supply chains and do we need new design principles and operations research models to support the network design.*

1.5.2 Research goal

The literature describes reverse supply chains mostly described as different from forward supply chains, see for example Fleischmann et al. (2000) and De Brito

(2003). It is argued that characteristics such as heterogeneity, uncertainty and low quality of returns make the reverse channel different from forward channels. This notion often seems to justify the development of special operations research (OR) models. However, we argue that the impact of characteristics of a reverse supply chain must be mapped first. Hence we focus on the so-called logistics concept, before deciding on the development of specialized OR models. A logistics concept comprehends the reverse supply chain strategy (an aspect that has received limited attention in literature), the network design, planning and control and IT choices (Van Goor et al., 1998). Also note that many of the studies in network design do not explicitly look into the consequences of these strategic decisions on the tactical and operational level. As has been shown in many other studies, the interaction between strategic, tactical and operational elements of the logistics concept is critical, see for example Le Blanc et al. (2004b). Once we have found the right logistics design principles, we can select the OR models to be used.
Eco-efficiency is the foundation of reverse supply chains, but this does not necessarily imply the need for new logistics concepts and OR models. In this research, we conduct an in-depth study on the special characteristics of reverse supply chains, from both a logistics concept point of view and an OR modeling perspective. The research deals with the strategic network design of the reverse chain and its interaction with tactical/operational routing concepts for reverse distribution and collection. The study will be based on cases from the ARN practice and an investigation of the modeling literature. An explicit comparison of forward and reverse supply chains is limited to the literature on the modeling level. The papers describing the application of mathematical models are typically detailed and comprehensive and thus provide an excellent source for comparison. In other words, we compare reverse supply chains only on an OR modeling level, without including logistics concepts from forward logistics cases.

The two goals of the thesis can be summarized as follows:

1. *To develop qualitative design principles for network design for eco-efficiency focused end-of-life management reverse supply chains.*
2. *To assess the need for developing specialized operations research models to support the design process in a quantitative manner logically connected to the qualitative design principles.*

1.5.3 Research questions

The research in this dissertation is based on the paradigm of business economics, and in particular operations research, as a design science. Design science is not descriptive, but prescriptive. It aims at helping practitioners by providing them with principles to design new or to improve existing systems (Van Aken, 2004). Typical

examples of design sciences are architecture and medical sciences, where fundamental research takes place to develop knowledge for professionals. This research took place on the borderline of science and practice. While incorporating practical knowledge accumulated in several company projects, the research is still based on scientific literature, seminars, conferences and discussions with leading scientists in the field.
This thesis aims at developing qualitative design principles for reverse supply chains, formulated as propositions. A proposition is the content of an assertion. Design principles are no exact algorithms that work in every instance; rather they are qualitative rules-of-thumb that work well on a group of instances in a certain domain (Van Aken, 2004). Besides by argumentation, the design of a reverse supply chain is supported by the use of mathematical models. We therefore also assess the modeling issues for strategic network design supporting the design principles.
This thesis poses the following research questions:

1. What are typical returns and typical reverse supply chains?
2. What are the determinants of an appropriate design for the reverse logistics concept?
3. How do other elements of the logistics concept, i.e. planning, control and IT, impact the choices in the strategic reverse network design?
4. How can design principles for strategic reverse network design be formulated as propositions?
5. Does the reverse logistics concept have distinguishing characteristics that justify the development of specific operations research models for network design?

1.6 Methodology and thesis outline

1.6.1 Operations research case studies using the regulative and reflective cycles

This research takes place in the field of reverse logistics, applying operations research, using a case study research approach. Both operations research and case study research are described briefly below.
Operations research is the discipline of using analytical methods to analyze complex real-world systems, typically with the goal of improving or optimizing performance. Operations research originates from the mathematical support in designing radar systems for the Royal Air Force during World War II (Keys, 1991). Today, operations research is among the major driving forces behind successful supply chain management (Informs, 2004) and therefore of interest to closed-loop supply chain management.

The research in this thesis is case-based. A case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between the phenomenon and the context are not clearly evident (Yin, 2003). The importance of case study research is demonstrated by the fact that many of the real breakthrough developments, such as MRP (material requirements planning) and JIT (just-in-time) techniques, took place in industry and do not stem from academic research (Bertrand and Fransoo, 2002). Meredith (1998) puts forward three reasons to conduct case studies. First, a certain phenomenon can be studied in its natural setting, with observations of actual practice. Second, the case study methodology focuses on identifying effect-cause relationships rather than just describing the effects. Third, it allows explorative investigation in situations where full understanding of a phenomenon and the variables is lacking.

Our methodology is based on regulative and reflective cycles as described by Van Aken (1994). In the regulative cycle, a (practical) problem is analyzed and solved, and the implications are evaluated, forming a case study. The regulative cycle represents the typical steps involved in a real-life operations research project as described by Fleuren (2001). Having completed a series of case studies, one can progress to the reflective cycle. In the reflective cycle, the solution techniques of the regulative cycle are generalized, yielding new insights. The main difference between the regulative and reflective cycles is that the regulative cycle is concerned with current practical problems, while the reflective cycle is concerned with not yet existing or elsewhere-existing problems with a similar structure. A critical issue is the optimal number of case studies and the generalizability of the results. Section 1.6.2 discusses this together with the other elements of the research strategy.

1.6.2 Research strategy design

Designing a research strategy using a case study methodology requires answering the following questions, adapted from Voss et al. (2002) and Yin (2003):

1. Do we adopt a single or multi-case study analysis, and what are the units of analysis?
2. How do we select the case studies?
3. How do we embed the case in relation to the general body of knowledge? Do we use the case studies for theory testing, theory refinement and/or theory development?
4. How do we assure the quality of the research design in terms of:
    a. Construct validity? This is the extent to which we establish correct operational measures for the concepts being studied.
    b. Reliability? This is the extent to which the case study's operations can be repeated.

   c. Internal validity? This is the extent to which we can form causal relationships.
   d. External validity? This determines how far the study's finding can be generalized.
5. What techniques do we use to link the findings of the case studies to the theory?

<u>Ad. 1: Single case study with multiple units of analysis</u>

This thesis describes three real-life case studies, all situated in the reverse network of Auto Recycling Nederland (ARN). Since the three real-life projects are related to each other and are part of the bigger network with one overall objective, we cannot consider the projects as "independent individuals" and thus as multiple case studies in the literal sense (Yin, 2003). However, a single case study still allows the study of several contexts. There is no clear definition of what constitutes a single case study or units of analysis (Voss et al., 2002). In our view, Auto Recycling Nederland is a single case study, and the three projects are the units of analysis. The choice for a single case methodology has its limitations in terms of generalizability, and biases can occur due to misjudging how representative the outcomes are (Voss et al., 2002). Caution is thus needed in the reflective cycle of Van Aken (1994). However, single case studies also have their merits. Our rationale for the use of a single case methodology consists of three parts. First, a single case methodology is more suitable for an in-depth analysis, which is necessary in view of our problem. Second, our case is a representative or typical case in terms of Yin (2003): the lessons learned from our case are valuable for organizations similar to ARN. Third, adopting multiple units of analysis strengthens the external validity of the case study (Voss et al., 2002).
The remainder of this thesis discusses case studies at the level of a reverse supply chain within a network, although, in the literal sense, we should be referring to it as a unit of analysis. Within each case in the ARN network we consider the following:

- The logistics concept, including a qualitative description of the system and the proposed changes.
- The current and future situation measured by several performance indicators, typically costs.
- The operations research models used in the analysis.

<u>Ad. 2: Selecting the case studies</u>

The case studies were selected in the network of ARN, which covers a wide variety of reverse supply chains, with varying characteristics, such as:

- High and low volume
- Driven by a negative externality or by economic value

- Time-critical versus non-time-critical

These different characteristics require different strategic focal areas, thereby contributing to the validity of the research for reverse networks managing end-of-life (EOL) returns.

Ad. 3: Embedding the cases in the general body of knowledge

The case study methodology can be used to pursue various aims: field exploration, theory formulation, theory testing, and theory extension (Voss et al., 2002). Yin (2003) advocates formulating propositions from theory and then applying case study research primarily for testing theories. Experiences from the cases can then subsequently be used to improve the initial propositions. Other authors, among them Eisenhardt (1989) and Voss et al. (2002), argue that case study research aims primarily at theory inducements, hence the formulation of propositions. Taking these elements together, we use case studies for theory extension and refinement, while formulating propositions based on the literature. Section 1.5 described the goal of the research and formulated research questions that provide the starting point for an extensive literature review. The literature allows us to deduce three propositions in Chapter 3. Three projects are conducted within the domain of end-of-life vehicle recycling managed by collective organizations, and solutions to real-life problems (“units of analysis”) are described in Chapters 4, 5 and 6. The study setting, the Auto Recycling Nederland network, is thoroughly reviewed in Chapter 2. The three projects, which we refer to as case studies, are executed using the regulative cycle in terms of Van Aken (1994). Using the case study experience, Chapter 7 reflects and refines the propositions into more general design principles for reverse supply chains. A proposition holds until proven to be false. Falsification can only occur based on case study observations.

Ad. 4: Quality aspects in research design

In our view, the four quality requirements, construct validity, internal validity, external validity and reliability, are interrelated. For example, sensitivity analysis strengthens not only construct validity but also the internal validity. To keep it simple, we describe the elements separately.

Fleuren (2001) describes the critical steps in an operations research project: problem definition, modeling, data collection and analysis, verification, validation and scenario analysis and, finally, implementation. By thoroughly following this protocol in our cases, we assure the construct validity.

The descriptions of the problem setting, the models, the modeling assumptions, the algorithms, data collection, scenario selection and the results are explicitly discussed in each case studies in order to assure the reliability of the research.

The internal validity is assured by careful selection of the cases (“units of analysis”). The reverse supply chains in the cases are part of the bigger network of ARN, with

one overall goal: compliance with environmental legislation in an efficient way. Eco-efficiency is the critical factor in determining the design of the reverse supply chain. Analyzing different units of analysis allows us to identify the causal relationship between network design and eco-efficiency more clearly on a meta-project level. Careful selection means that the three cases must have sufficient variety (polarity) to establish the causal relationships. The causal relationships concern the elements and determinants of the logistics concept and the operations research models.
The external validity is assured by the selection of ARN as a representative case for end-of-life management in a collective solution, executing the extended producer responsibility. The characteristics of the class of problems that ARN represents are summarized in Table 1.1.

Table 1.1. Characteristics of the typical situation considered in this study.

Phase in the product life cycle:	End-of-life
Type of product:	Durable products with limited residual value
Dominant recovery option:	Material recycling
Way of organizing:	Collective system executing the EPR
Drivers:	Environmental legislation with strict recycling targets

We consider analytical generalization of the results to similar situations. Statistical generalization is not applicable, since too many cases would be required (Yin, 2003). Generalization of the insights obtained from the ARN case is possible in the following directions:

- In other industries to similar organizations, executing producer responsibility in a certain area on behalf of the OEMs, which are quite common. See for example the European Recycling Platform (2005) and De Koster et al. (2005).
- In the same industry, where systems for ELV recycling are built or restructured. Due to progressive legislation in the Netherlands, ARN is ahead of the developments in other countries.

Ad. 5: Linking the findings of the case studies to the theory

The case studies are used for the reflection on the propositions, deduced from the literature, that are formulated in Chapter 3. The design principles developed are by default applicable to end-of-life management of automobiles. All three propositions are covered within all three cases. By pattern matching, the case outcome is compared to the predicted outcome. Explanation building is the process of analyzing the case by building an explanation for the outcomes (Yin, 2003). We use pattern matching by comparing our initial propositions to the outcomes of the cases. Explanation building is used to develop new theory with a clear analogy to theory in forward supply chains. This results in refined design principles for reverse supply chain design.

Because we consider ARN as an embedded, or typical, case for end-of-life product management, we consider it feasible to develop theory and to generalize our propositions to other EOL systems in other industries. Generalization to other types of returns is more difficult. In a single case study research design, the replication logic is not applicable. Further research and more case studies thus need to be conducted, paying attention to generalization issues.

1.6.3 Outline of the thesis

Figure 1.6 presents an outline of the thesis, including the main methodological steps.
Chapter 2 introduces Auto Recycling Nederland, since this is the organization where the case studies took place. Repeating case studies is difficult due to intangibility in the everyday business life. Therefore, a detailed description the organization and its background will shed light on the understanding and reasoning behind certain decisions. Chapter 3 provides a detailed literature review, resulting in the formulation of propositions. Chapters 4, 5 and 6 describe the business cases. The cases consider, respectively, the network redesign for recycling LPG-tanks, the development of a planning methodology for the collection of waste oils and fuels, and an analysis of the use of advanced planning concepts in a container network. Cross-case reflection on the case studies is provided in Chapter 7, resulting in a revision of the propositions and a formulation of newly developed design knowledge. Chapter 8 concludes this thesis by summarizing, indicating further research and looking to the future of closed-loop supply chains.

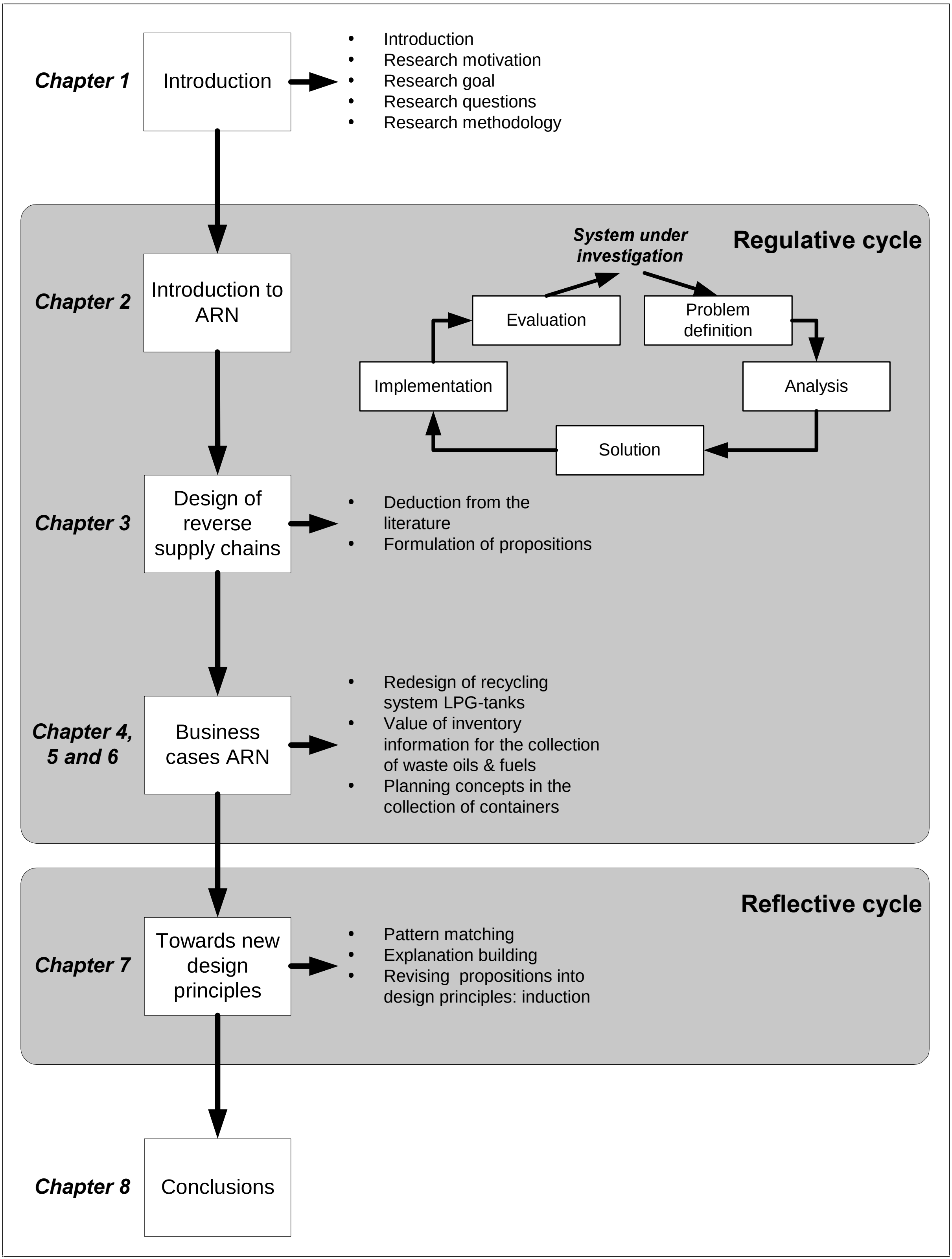

Figure 1.6. Overview structure.

Chapter 2

Auto Recycling Nederland

"Ik zal bovendien een paar geleerden inschakelen, men zegt dat de wetenschap ver is gevorderd in de vernietigingstechniek!"
Burgemeester Dickerdack (2851)

This special chapter describing Auto Recycling Nederland (ARN) has several purposes. Many of the examples that will be given in Chapter 3 to clarify the theory, stem from the everyday practice of ARN. Furthermore, the in-depth case studies in chapter 4 originate from Auto Recycling Nederland. Detailed descriptions of the context and background of case studies are necessary in order to understand the implications.

2.1 Historic perspective

In the past, a large number of small end-of-life vehicle (ELV) dismantlers with low technological sophistication handled the treatment of end-of-life vehicles in the Netherlands (Bebelaar et al., 2004). Their existence was based on the trade in spare parts and metals. Generally, dismantlers refrained from investing in equipment for the handling and disposal of hazardous automotive substances such as solvents and oils (Orsato et al., 2002). The dismantling activities were practiced in the open air without any awareness or care for the environment. Environmental and safety legislation was absent. In the beginning of the 1980s, the Dutch government called a halt to this undesirable situation by introducing environmental and safety legislation. Many dismantling companies, unable to cope with the strict legislation, abandoned their dismantling activities. Within 20 years, the number of permits was reduced from about 3,000 to approximately 900. Dismantlers that followed the environmental and safety requirements owned the remaining permits; as a result, their reputation with the public improved.

2.1.1 ARN: a joint industry effort

In the beginning of the nineties, concern for the environment was growing. Cars, in particular, were considered to be one of the largest polluters in modern society. The Dutch ministry of housing, spatial planning and the environment came up with the idea of a recycling fee for new cars. The money should be deposited into a fund managed by the government for reducing the environmental burden caused by road traffic in general, and end-of-life vehicles in particular. The automotive industry, represented by the Dutch society of automobile importers (RAI), did not like the idea, since money deposited in the fund was no longer under their control. In 1993, the Dutch automotive industry decided to act proactively and to take responsibility for end-of-life vehicles into their own hands. Auto & Recycling was founded by the Dutch branch organizations in the automotive industry:

- RAI, society of car manufacturers and importers
- BOVAG, society of car dealers and workshops
- STIBA, society of car dismantling companies
- FOCWA, society of damage repair companies

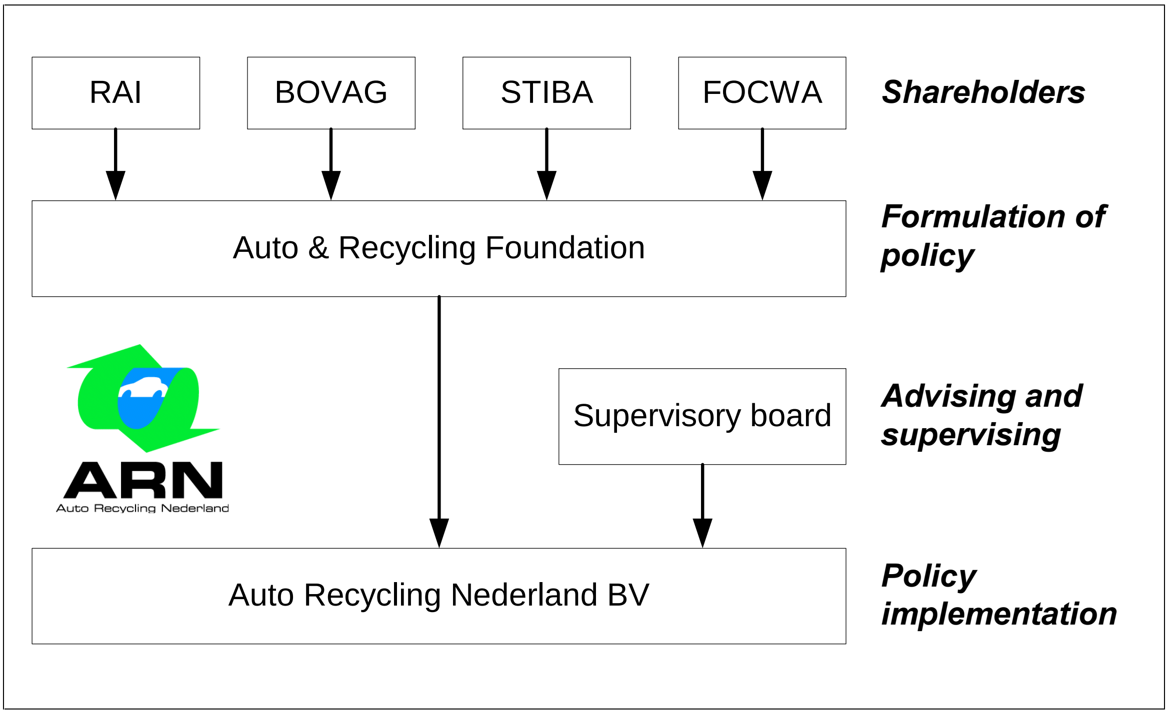

Figure 2.1. Organizational structure of Auto Recycling Nederland.

The Auto & Recycling foundation owns the working company Auto Recycling Nederland (ARN), responsible for the recycling of end-of-life vehicles. As a consequence of this arrangement, ARN is a collective and consensus-based organization. ARN represents parties in the automotive industry involved in each phase of an automobile’s life cycle. In earlier stages than end-of-life, automotive waste products are released. Therefore, in the future, the participation of organizations representing the interest of garages, workshops and damage repair companies, can result in opening the channels of ARN for materials and components disposed during service and repair activities. Figure 2.1 provides an overview of the organizational structure (Auto Recycling Nederland, 2003).

The main function of ARN is the coordination, control and funding of the recycling activities for ELVs such that ARN fulfills the legal requirements on behalf of the Dutch automotive industry. To achieve this, ARN has built partnerships with ELV-dismantlers, specialized logistic service providers, recyclers and shredders. The system is operational since 1995. The basic principle of the ARN system is the focus on activities that are economically not sustainable but are necessary for the automotive industry to fulfill the legal requirements.

2.1.2 Achievements

Since the foundation’s creation almost 2.5 million cars have been recycled through the ARN system. This corresponds to approximately 275,000 vehicles per year, resulting in a market share of more than 90%. ELV-dismantlers that are not affiliated to ARN collect the remaining 10% of ELVs. The recycling of these cars is essentially driven only by economic motivation, such as trade in spare parts and the metal content, resulting in a significantly lower degree of recovery (Kanari et al., 2003).
ARN controls a countrywide network of 270 ELV-dismantlers, collecting ELVs from consumers free of charge, as required by European legislation. Legislation also requires the reporting of so-called mass balances, showing the relation between inputs and outputs and thereby the achieved recycling quota.
Table 2.1 shows a summarized mass balance of ARN over the period 2001 – 2004 (Auto Recycling Nederland, 2002, 2003, 2004 and 2005).

Table 2.1. Mass balance of Auto Recycling Nederland for 2001-2004.

	2001	2002	2003	2004
Average weight ELV (kg)	912.5	915.9	911.0	915.0
Metals (kg)	684.4	686.9	683.3	686.3
ARN Materials (kg)				
material recycling	84.7	85.0	84.9	76.9
thermal recycling	15.5	15.6	15.6	18.3
Recycling realization (kg)	784.6	787.5	783.8	781.5
	86.0%	86.0%	86.0%	85.4%
Rest fraction (kg)	127.9	128.4	127.2	133.5
	14.0%	14.0%	14.0%	14.6%

With the achievement of this recycling target of 85% already in 1998, ARN has a leadership position in the world. The effectiveness of the Dutch way of treating end-of-life vehicles has inspired policy makers in the European Directive.

2.2 The European Directive on ELVs

The end-of-life vehicles directive (2000/53/EC) was taken into European law in October 2000. This directive aims at improving environmental performance of all entities involved in a vehicle life cycle and especially the treatment of ELVs. Basically, it concerns the prevention of waste coming from vehicles and promotion of reuse, recycling and recovery of ELVs and their components. The articles of the European Directive are summarized in Table 2.2.

Table 2.2. Summary of the articles in the European Directive 2000/53/EC on end-of-life vehicles (ELVs).

Prevention (article 4)	• New vehicles are designed and produced bearing in mind dismantling, reuse and recycling. • Manufacturers increase the content of recycled materials in cars. • Manufacturers limit the use of hazardous materials: vehicles put on the market do not contain lead, mercury, cadmium and hexavalent chromium.
Collection (article 5)	• The last owner can hand in the ELV free of charge to a licensed treatment facility and is provided with a certificate of destruction. • An adequate network is available for collection of ELVs.
Treatment (article 6)	• There must be a licensing system for treatment facilities of ELVs. • All ELVs should be stored and processed in accordance with the minimal environmental and safety requirements. • Hazardous materials and components are removed and segregated to prevent contamination of subsequent shredder waste.
Reuse and recovery (article 7)	• From 2006, the ELVs will be recycled for at least 85% of the average vehicle weight, with at most 5% by incineration with energy recovery. • In 2015, the recycling target will be raised to 95% of which at most 10% by incineration with energy recovery.
Coding standards and dismantling information (article 8)	• It is compulsory for manufacturers to use standards for coding components and materials to facilitate identification for reuse and recovery. • For each new vehicle type, the manufacturers provide the required dismantling information (a recycling passport) to all authorized treatment facilities.
Reporting and information (article 9)	• Member states report to the European Commission on the structure for treatment of ELVs and the possible economic distortions of competitions between the member states. • The producers ensure that information on the recoverability and recyclability of cars is accessible for consumers.

The European legislation sets a framework for the national legislations. All member states must embed the EU directive in the national legislation, taking into account the specific national circumstances. All of the fifteen countries of the “old” European Union have taken steps towards implementation; a detailed overview on the requirements deviating from the EU directive and the status of implementation can be obtained from ACEA (2004). In the Netherlands, the European Directive was implemented in 2002 in the “management of end-of-life vehicles decree” (Besluit Beheer Autowrakken, 2002).

The directive caused tensions among the car manufacturers (Sakkas and Manios, 2003). According to the industry, the directive does not focus enough on the product life cycle. The end-of-life phase of a vehicle represents less than 5% of the total life cycle impact (Schmidt et al., 2004). The composition of cars has changed

dramatically over time due to increasing demand for safety, lower fuel consumption, less air emissions and noise reduction. Lighter weight and more economical cars consist of many plastics that are difficult to recycle; heavy cars made of steel are, however, easy to recycle. The recycling of metals can drive a financially self-sustaining system. However, the amount of metals in the ELVs has decreased from about 90% in 1955 to about 75% in 1998 (Bebelaar et al., 2004). According to OEMs, this has led to an irresolvable conflict of aims (VDA, 2003). The key to successful recycling lies in the further processing of the shredder residual, and specifically in the recovery of plastics in this process (Bellmann and Khare, 1999). Developments in this technology have evolved rapidly, and a recycling yield of about 90% is achievable with the use of post-shredder technology (PST), if good market opportunities exist for recycled materials (Bebelaar et al., 2004).
By setting minimum requirements for the national legislations, the EU directive aims at harmonization. Individual member states interpret the European rules differently, however, and take diverse measures, resulting in a dispersed system. For cost efficiency and environmental effectiveness, it seems more desirable to further harmonize the rules and legislation such that pan-European recycling systems can be built.

2.3 The reverse chain of Auto Recycling Nederland

The main function of ARN is the coordination, control, reporting and funding of the recycling activities for ELVs. The coordination function deals with the management of operational processes, which is discussed in 2.3.1. The control function corresponds with the management of information flows and is used for reducing potential conflicts of interests and reporting to stakeholders. This is discussed in 2.3.2. The funding of the activities takes place according to the amount of material claimed and handed over to the next element in the chain, resulting in financial flows through the network. This is discussed in 2.3.3.

2.3.1 Coordinating the operational processes

The consumer can hand in his or her ELV free of charge at one of the 270 ELV-dismantlers affiliated to ARN. The vehicle is removed from the vehicle register and a certificate of destruction is provided to the last owner. Within ten working days after vehicle deregistration, the so-called hazardous materials (such as oils, batteries and LPG-tanks) must have been removed from the ELV. This is called the de-pollution process. To prevent ground contamination, vehicles must be stored on impermeable floors until de-pollution has taken place. After de-pollution, the dismantler is free to remove spare parts and materials and put them on the market, since reuse is considered better than material recycling. The trade in spare parts is lucrative. To support the trade in spare parts, the ELV dismantlers have jointly set up a call center and a central database providing information on availability and prices. Some insurance companies offer green insurance policies to customers when their damaged cars are repaired with used parts (Stiba, 2004). Engines of relative young scrap cars are removed and sold to overhauling companies for recovery processes such as described in Van der Laan (1997), Seitz et al. (2003) and Seitz and Peattie (2004). It is even allowed to reuse fuels drained from ELVs, since all taxes have been paid for these fuels. The removal of certain materials and parts that cannot be traded by ELV-dismantlers is stimulated by a premium paid by ARN. Depending on their nature, these “ARN-materials” are stored in equipment, such as containers, box-pallets or vessels, provided by ARN. Table 2.3 provides an overview of the ARN materials together with the average amount per ELV, the packaging used for storage and transportation and the final way of recovery. When a certain amount of materials is gathered, the logistics service provider is contacted for an appointment to collect the materials. These logistics service providers are specialized in the transportation and handling of waste and recyclables. The materials are consolidated at the depots of the logistics service providers in order to obtain better economies of scale for transportation to the contracted recyclers. The delivery to the recycler is the end-point of the reverse chain for ARN. The recyclers then process the materials according to the processes agreed upon with ARN, and assure the remarketing of the recovered materials or products.

After removal of the ARN materials at the ELV-dismantler, the remainder is a carcass or hulk. The dismantler trades the hulks either directly or via intermediaries to one of the shredders in the Netherlands, Belgium or Germany. The carcasses are shredded and the material fractions are separated and sold on the resource market. Nijkerk and Dalmijn (1998) describe the types of processes within a shredder plant. The separated iron fraction, for example, can be used as a resource in new steel production and substitutes iron ore. The residual fraction that remains after the post-shredder separation phase is dumped at landfill sites. Today, this is about 14% of the average weight of the ELV; in the near future, when more sophisticated mechanical separation techniques will be available, this will be reduced to about 5-10%.

Figure 2.2 provides an overview of the network.

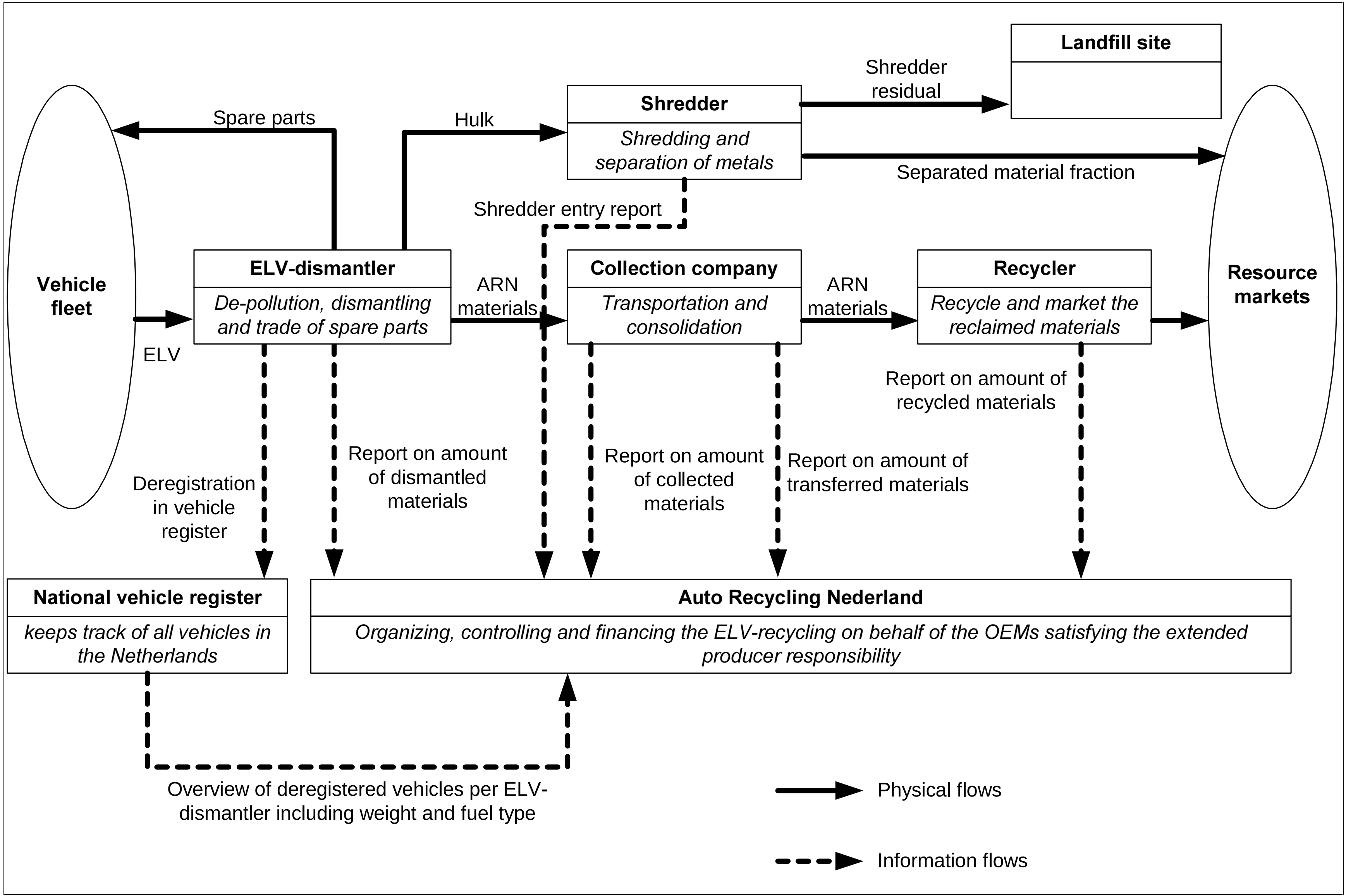

Figure 2.2. An overview of the physical and information flows in the ARN network.

Table 2.3. Overview of the ARN materials (descriptions of the way of recovery based on the ARN environmental report 2002).

Material	Standard quantity	Packaging	Way of recovery
Batteries	13.3 kg	Battery boxes	Batteries consist of battery acid, the plastic casing and lead. These three materials must be separated from each other during processing. Each of them will find a new use, with the lead being reprocessed for recycling in new batteries. A portion of the plastic is reused in various applications, such as in batteries, while the battery acid is neutralized.
Brake fluid	0.3 l	Barrels	All of the mineral oil is extracted from the brake fluid before the water is removed. The result is a product that can be used by brake fluid manufacturers for new brake fluid.
Bumpers	27.9 kg	Container	The only bumper shells suitable for further processing are those made of polypropylene (PP) or polycarbonate (PC). Bumpers made of other materials are left in place. The PP and PC bumpers are separated manually. During the recycling process, PP and PC are reclaimed in as pure a form as possible. The PP and PC components are used to manufacture, among other items, engine covers, wheel arches and plastic parts for the heating systems in new cars.
Coconut fiber	0.5 kg	Pallet	The coconut fiber is shredded into individual fibers before magnetic tape is employed to extract any metal components. The fibers are mixed with additives and pressed into sheets that are used as acoustic insulation in doors, for instance.
Cooling fluid	3.6 l	Storage vessels	Cooling fluid contains monoethylene glycol (MEG), which is reclaimed from the cooling fluid by means of distillation. The reclaimed MEG is mixed with water and additives to form new cooling fluid. MEG is also used in solvents for the paint industry and in cleaning products.
Fuels	5.0 l	Storage vessels	After petrol and diesel have been decontaminated, they are used as secondary fuel for soil purification plants.
Glass	25.4 kg	Compartment in trio- container	Glass is crushed, and any metal components are magnetically extracted. Plastic ingredients (laminated glass film) are blown from the mixture. The remaining glass can be used for a number of different applications, including glass fiber and (GRP) bumpers. The glass is also used as a raw material for bottles and sheet glass.
Grilles	0.5 kg	Box pallet	The ABS from grilles is purified to the greatest extent possible during the recycling process, and is generally used in household appliances.
Hubcaps	0.7 kg	Box pallet	Hubcaps consist of various types of plastic. Hubcaps are sorted according to the type of plastic and shredded. The polyamides and ABS are used for the plastic parts of computer monitors.

Material	Standard quantity	Packaging	Way of recovery
Inner tubes	0.1 kg	Box pallet	Inner tubes are shredded, and the butyl or natural rubbers from which they are made are sorted. De-vulcanization is employed to reduce the rubber to its original chemical structure, rendering it suitable for new products. Butyl rubber is used to cover the inside of tires to make them airtight, whereas rubber is recovered for the manufacture of rubber boots.
LPG-tanks	0.06	Racks	Gas is extracted from LPG tanks, and the pure LPG is stored for reuse as fuel. The empty tanks and fittings can be sold as part of an LPG installation or as scrap for metal recycling purposes.
Oil	4.9 l	Storage vessels	Oil is turned into base oil, high-grade fuels and flux oil. Base oil is the primary raw material for new lubricants and motor oil. Flux oil is a tar-like substance suitable for use in roofing material and road construction.
Oil filters	0.5 kg	Barrels	The oil filters are shredded; the metal is magnetically extracted and recycled for the steel industry. The oil is pressed out of the paper and refined, whilst the paper is used as a secondary fuel.
PU foam	6.7 kg	Compartment in trio-container	PU foam is shredded into flakes. The shredded foam is mixed with other types of fabric to be processed into synthetic fleece and lagging for use in new cars. The PU foam flakes can also be mixed with glue to be pressed into large blocks that can be cut into shape for car seat padding, mattresses, sports mats, cow mats and furniture.
Rubber strips	7.7 kg	Compartment in trio-container	Cement kilns and/or power stations use most of the rubber strips as fuel to reclaim energy. Shredded rubber strips with few impurities are also recycled as roll container wheels.
Safety belts	0.35 kg	Box pallet	Safety belts are chopped into small pieces and mixed with other materials. The mixture is then used as raw material for products such as synthetic fleece used to cover springs in the furniture industry. A small proportion of safety belts are used in their original form as webbing for tree ties.
Tires	27.9 kg	Container	Some of the tires will be good enough to be reused right away or are retreaded. Some of the low-grade tires are shredded, after which the fabric and metal content are removed, leaving a rubber granulate used in the production of rubber paving tiles and insulation mats, and as underlay material on sports fields. A large proportion of the tires are used as fuel by the cement industry.
Windscreen washer fluid	1.0 l	Storage vessels	Windscreen washer is treated in the same way as cooling fluid, by distillation. With windscreen washer fluid, the various types of alcohol are separated and sold in their pure forms for reuse in a number of industrial applications.

2.3.2 Control and reporting

Since Auto Recycling Nederland is responsible for all the processes, several types of feedback mechanisms have been installed to enable ARN to trace each ELV and every kilogram of material. Figure 2.2 exhibits the necessary information flows from the operational processes. This starts with a daily report on the deregistered ELVs of all affiliated dismantlers, which ARN obtains from the National Vehicle Register (RDW). These data are detailed to the level of registration number, brand, type, empty vehicle weight and fuel type. The ELV-dismantler is allowed to claim a premium at ARN based on the actual weights, with a maximum quantity, the so-called standard quantity, as shown in Table 2.3. ARN can adjust the standard quantities and premiums periodically, for example when the composition of cars changes or the dismantling methods are improved for higher yields. The logistics service provider provides a weight bill to the dismantler when the materials are collected. Based on the standard quantities and the weight bill, ARN can check whether the claimed quantities are reasonable. Each quarter, the logistics service providers provide a detailed report to ARN, considering the quantities collected from each ELV dismantler, the inventory position at the depot and the transportations to the different recyclers. Similarly, the recyclers provide reports on the amount of materials received. Thus, the mass of materials in the system can be completely traced: what comes in must go out, and the flows of ARN materials is thus closed and controlled. In addition to control over the flow of ARN materials, a control loop is also necessary for hulks. Therefore, ARN, together with the shredder companies, set up the so-called shredder intake control in 2002. This is interesting not only for ARN, but also for shredders, since accepting only clean wrecks for shredding significantly reduces the amount of shredder waste. For ARN, it ensures the total chain management and a control mechanism to check whether ELV-dismantlers have indeed removed all ARN materials. An ELV-dismantler is obliged to mark each ELV with several barcodes. At the entrance to the shredder, the operators scan the barcodes on the ELVs and fill out electronic checklists on the condition of the ELVs. These shredder entry reports are sent electronically to ARN on a daily basis.

All of these information flows together facilitate the appropriate control on the activities in the network. A closed and controlled chain is required in order to justify the recycling percentage. In 2005, the European Commission will publish a formal methodology for the calculation of recycling realization that enables comparison and measuring compliance of the various member states. Until the publication of this methodology, ARN uses a methodology based on the realized quantities of ARN-materials collected and transferred to the contracted recycling companies. Figure 2.3 demonstrates the way the recycling realization in the ARN system is calculated. The average weight of the ELVs is known from the data of the vehicle register, and the average metal content and shredder residual is estimated based on research at the shredder facilities. The methodology, consistent with the compliance monitoring procedure proposed to the European Commission by Sander et al. (2002), is periodically checked and approved by accountants.

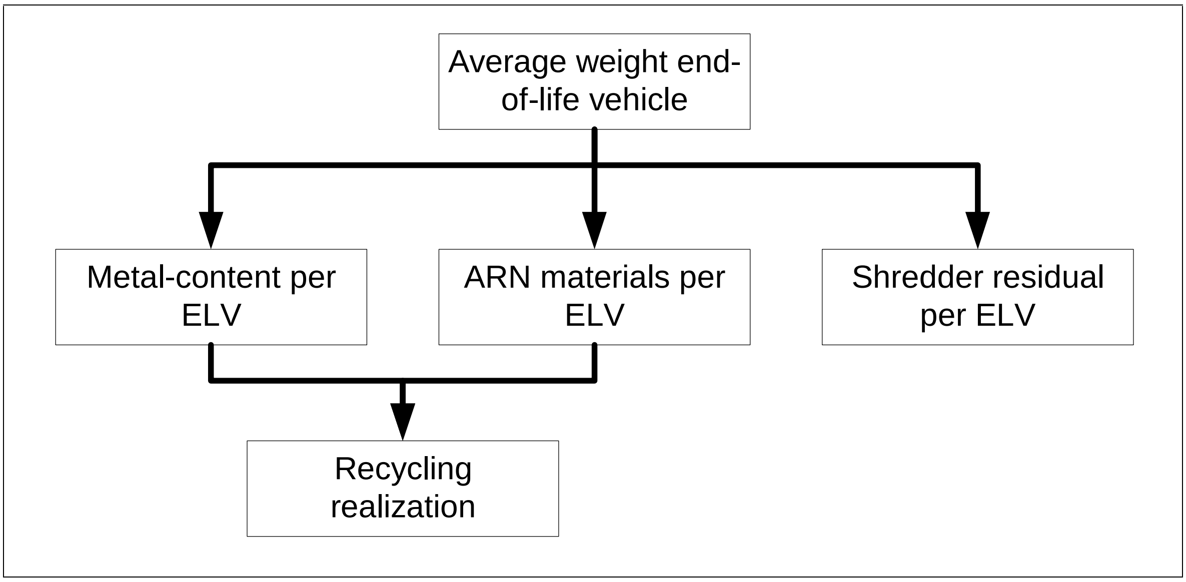

Figure 2.3. Diagram for calculation recycling realization (adapted from Auto Recycling Nederland, 2003).

2.3.3 Funding of the system

To finance all activities that are performed in the ARN chain, a waste disposal fee is raised on every new car sold. This fee, currently € 45, is generally declared binding in the Dutch Environmental Management Act until 2007, and payment of the fee is a necessity for obtaining a registration number. Using this fee, ARN finances the activities for the ARN materials of the ELV treatment, which means dismantling, collection and recycling. The amount that ARN pays to ELV-dismantlers is comprised of the cost of dismantling and gathering the necessary equipment, together with a small profit to stimulate the ELV-dismantler to actually perform the activities for ARN. To be able to keep track of the financial flows, the tariffs are passed on from entity to entity, with each taking its part of the tariff. ARN pays the premium per kilogram or liter material to the ELV-dismantler (tariff paid to ELV-dismantler = $\alpha + \beta + \gamma$), containing the negotiated tariffs for collection, consolidation and transportation to the recycler by the logistics service provider and the fee for recycling for the specific type of material. The dismantlers pay a tariff per kilogram or liter material to the logistics service provider (tariff paid to logistics service provider = $\beta + \gamma$), while the logistics service providers either pay a tariff to, or receive a tariff from (some materials have a positive residual value) the recyclers (tariff paid to recycler = γ). These tariffs are negotiated during a so-called tendering procedure. The tariffs are fixed after the tender, except for cost-indexation, for a period of three years. In the tender procedure, the logistic service providers are asked to bid on a contract for servicing a certain district for a certain material. Similarly, recyclers are asked to bid for processing certain materials. Based on the bids and qualitative judgment, coming from analyzing questionnaires, ARN selects a logistics service provider and a recycler for each district for each material. The financial flows in the network are described in Figure 2.4.

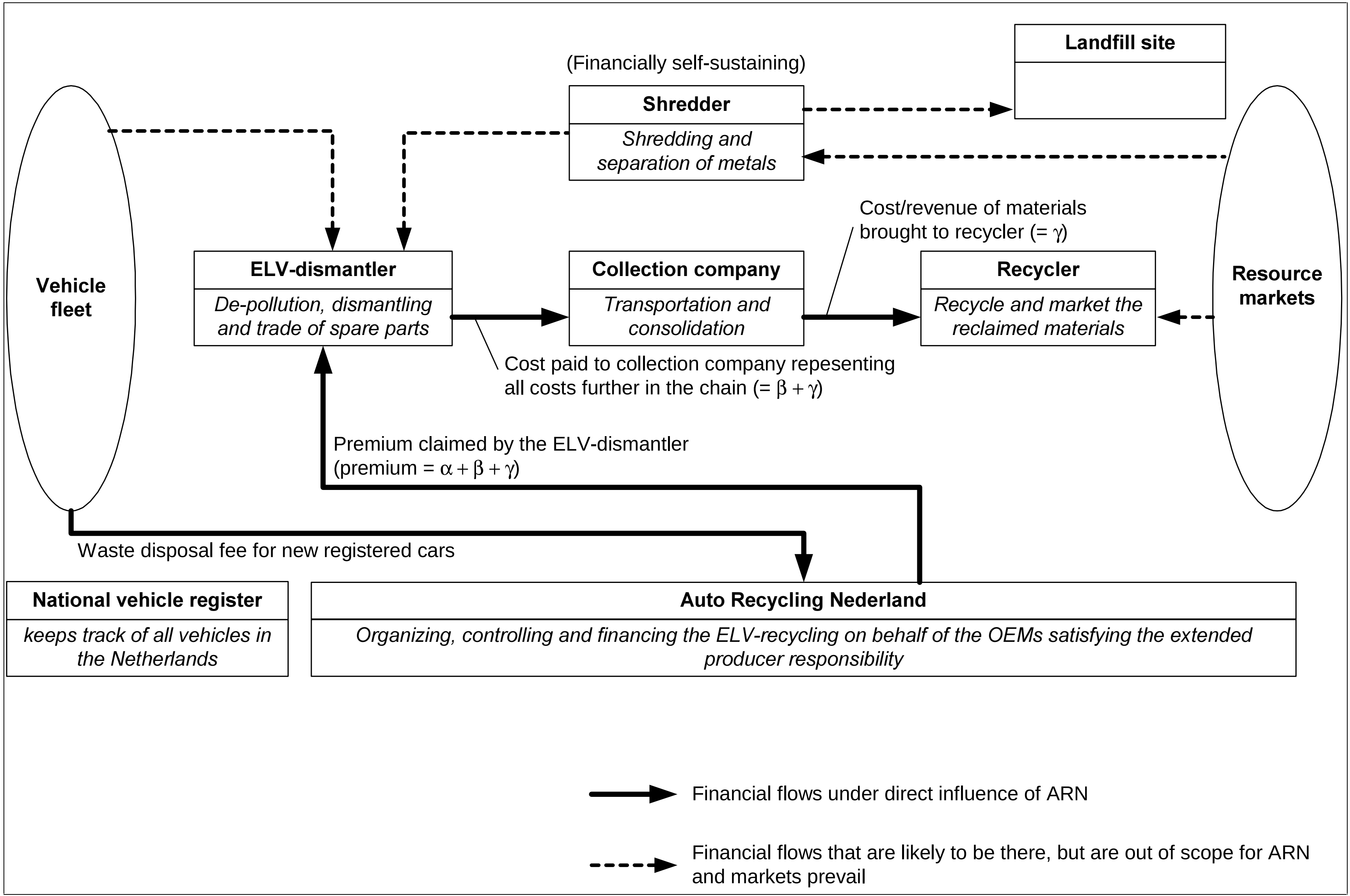

Figure 2.4. Financial flows in the ARN network.

2.4 ARN and the automotive industry

Section 2.5.1 discusses the view of the automotive industry on the ELV recycling business. Section 2.5.2 elaborates on the relationship between ARN and the mainstream automotive industry.

2.4.1 The perspective of the automotive industry on end-of-life vehicles

The recycling of ELVs is not part of the business horizon of OEMs. The involvement of the car manufacturer and its supply chain diminishes over the product life, as illustrated in Figure 2.5. During the production, distribution and sales phases, the involvement is maximal. During the first years in the use phase of the car, a warranty still applies, maintenance takes place by OEM dealers. As cars get older, the OEM dealers perform less of the maintenance and repairs. A ten-year-old car is likely to be serviced not by the official workshop of the dealer, but by mostly cheaper generic workshops. When the car is disposed, the extended producer responsibility again makes the OEM responsible for 100%.

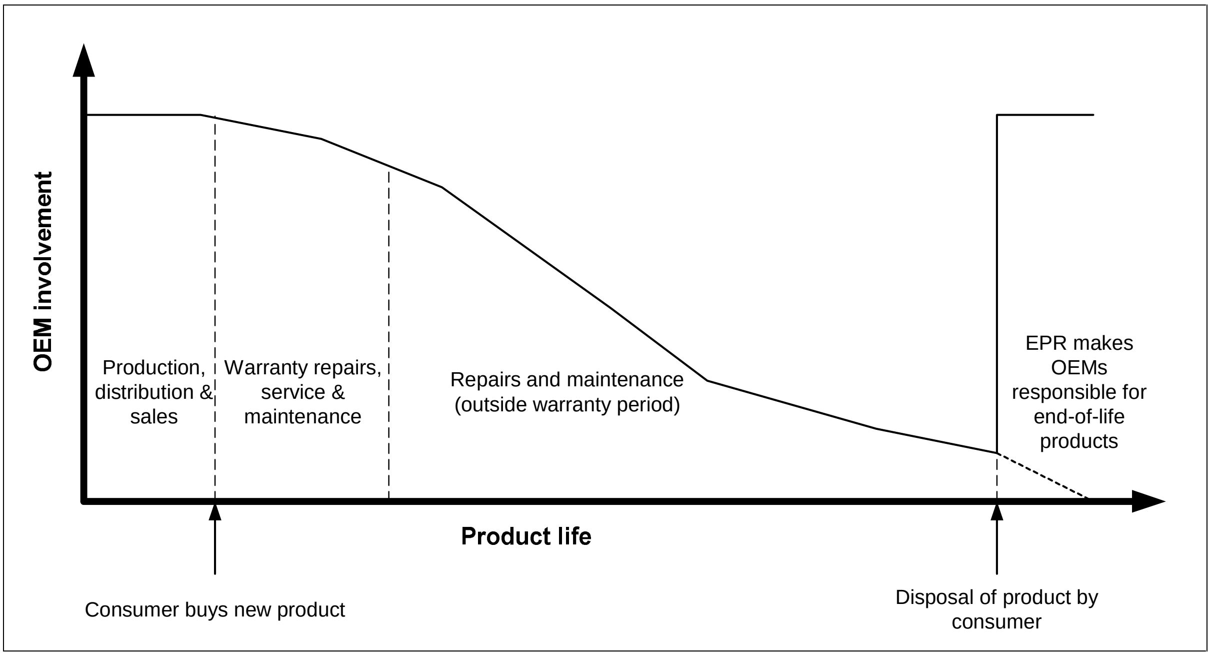

Figure 2.5. The OEM involvement over the product life.

The declining involvement with the customer and his or her car is undesirable from the viewpoint of the car manufacturers, since a large part of their revenues are downstream in service, parts and ancillary products; according to Ealey and Troyano-Bermúdez (2000), this can amount to even 60%. From the perspective of the OEM, the responsibility for the disposal of ELVs is somewhat strange, since the OEM's responsibility decreases as the car ages. Third-parties cannibalize their profits on cars at the end of the products life cycle, but these third-parties are not compelled to take any responsibility for end-of-life disposal.

Traditionally, the processing of end-of-life vehicles was the business of companies trading in metals and spare parts coming from ELVs. Spare part trading cannibalizes the profits of the OEMs, since it takes over the spare part sales in the course of the product life cycle. In some extreme cases, this even could damage the brand's reputation, since bad quality and unsafe parts coming from disreputable ELV dismantlers still contain the OEM brand name. With the improvements in the ELV-dismantling sector in the 1990s, OEMs recognized the potential in spare parts coming from ELVs. OEMs have therefore formed partnerships with some ELV-dismantlers. BMW, for example, has contracted ELV-dismantlers that deliver carefully dismantled spare parts for remanufacturing (De Graaf, 1999).

Even if the producer were responsible for de-pollution and recycling of the ELV, it would have the right to determine how and when this is done. Some manufacturers therefore desire a system in which ELV-dismantlers obtain the ELV from the manufacturer for free; since the residual value of ELVs is positive (due to large metal fractions), all the necessary de-pollution activities can be financed from the revenues.

2.4.2 ARN's relationship with the automotive industry

The relationship of Auto Recycling Nederland with the automotive industry is somewhat controversial. From an environmental perspective the ARN system has turned out to be successful: the recycling target of 85% of the average vehicle weight was reached in 1997. This directly influences the targets set in the European Directive. With ARN as an EU showcase, the directive forced the industry to put serious effort into ELV recycling everywhere in the European Union. More specific, the automotive industry seriously criticized the ARN system (Arge Altauto, 2002). The ARN system was even accused of causing market disruptions. An EC investigation in 2001 invalidated this accusation (European Commission, 2002).

The main points of criticism by the car manufacturers on the ARN system are as follows:

- The ARN system consisted of a large number of relatively small ELV-dismantlers processing about 1,000 wrecks. Economies of scale in the dismantling of ELVs are possible, and an optimal plant size of 4,000 to 6,000 ELVs is suggested (Sakkas and Manios, 2003).
- The 86% recycling quota in the ARN system is achieved by manual, and therefore expensive, dismantling of materials that marginally contribute to the recycling quota, such as grilles and PU foam. Mechanical separation of material fractions after shredding the wreck is cheaper.

- The ARN system is based on premiums paid to ELV-dismantlers to do the work; the overall residual value of an ELV is positive, however, due to large metals content.
- The ARN system is a collective solution without differentiation in the disposal fee, which does not encourage design for recycling or disassembly.

Despite this criticism, contacts between ARN and the automotive industry are good. The national representatives united in the RAI are part of the system, and transferred the responsibility of recycling activities to ARN, who managed the recycling process completely, from an environmental point of view. ARN must face the challenge however, of making the system more cost-efficient. If no serious actions are taken, the current three-year period might be the last period of generally declared binding waste disposal fee, since the Dutch government requires commitment of the industry. If this happens, the manufacturers will be allowed to set up their own recycling structures in the Netherlands. Such a development might even fit into the strategy of large manufacturers to develop brand-specific pan-European recovery networks. To a large extend, the issues that will be faced by the manufacturers in this situation, will be similar to the issues faced by ARN in the current system.

How this situation will develop is yet unclear. ARN and the automotive industry both face the same European legislation, with the recycling target of 95% in 2015, and both question the attainability of this goal. Ideally, the automotive industry and ARN will together work towards a European solution: extending the mean and lean forward supply chain for automobiles, with a reverse chain based on life cycle considerations in order to achieve a real closed-loop supply chain that will bring sustainable mobility to society.

Chapter 3

Design of reverse supply chains

"Ik mijmer. Grote gedachten stormen door mijn geest."

Olivier B. Bommel (3050)

This chapter deals with the research questions formulated in Section 1.5 from a theoretical viewpoint, summarized as follows:

1. What are typical returns and typical reverse supply chains?
2. What are the determinants of an appropriate design for the reverse logistics concept?
3. What is the impact of other elements of the logistics concept, i.e. planning, control and information technology, on the choices in the strategic reverse network design?
4. How are design principles for strategic reverse network design formulated as propositions?
5. Does the reverse logistics concept have distinguishing characteristics that justify the development of specific operations research models for network design?

The chapter results in design principles for reverse supply chains, formalized into propositions.

3.1 Introduction: the reverse logistics concept

A company's mission and vision must be reflected in its supply chain strategy. In the absence of a good supply chain strategy, new ideas and technologies cannot be successful (Fisher, 1997). The supply chain design depends on the consistency in dealing with product-market combinations, which must lead to a deliberately chosen network structure with a related control structure (Hoekstra and Romme, 1994). From the network structure, the planning, control and information infrastructure to coordinate the processes are determined. This chapter takes the logistics concept of Van Goor et al., (1998) as the starting point to develop the design principles for reverse supply chains. It identifies the impact of typical reverse supply chain determinants on the reverse supply chain strategy and, ultimately, on the reverse network design. Moreover, the concept comprises the interaction between network design and the other elements of the logistics concept: planning, control and IT. Figure 3.1 exhibits this top-down hierarchical approach, referred to as the logistics concept. A logistics concept must contribute to the overall business strategy and objectives, taking into account a number of given determinants, e.g. supply and demand characteristics, environmental legislation, social aspects and product characteristics.

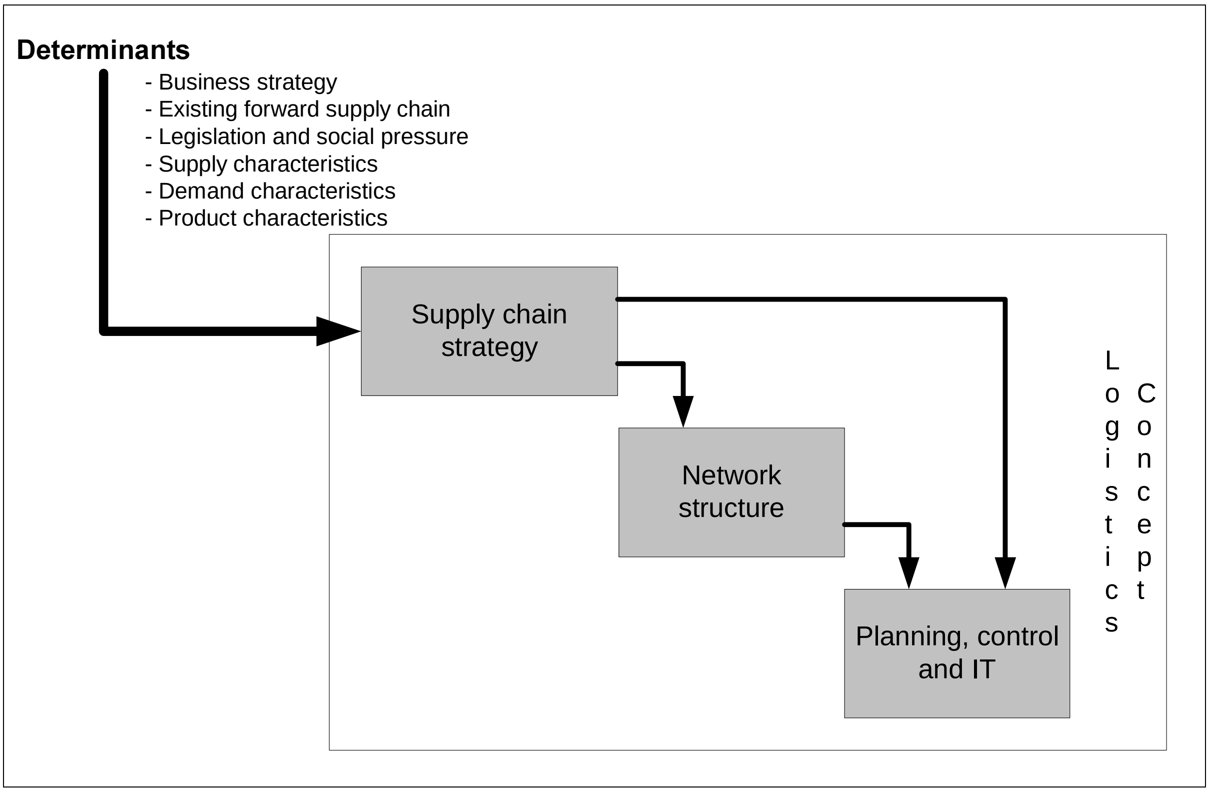

Figure 3.1. Logistics concept (Van Goor et al., 1998).

In order to develop design principles for reverse supply chains, we create a sound basis by the logistics concept as described above. Once these issues are mapped, we are equipped to discuss the adjustments in operations research (OR) models that might be needed for reverse supply chains particularly with respect to reverse supply chain network design. The typical reverse supply chain determinants provide the possible motivation for the development of new design principles and hence models.

Since our focus is on the network structure, we pay less attention to the planning, control and IT. Note that we define the network structure as the strategic physical network design together with tactical chain orchestration decisions, e.g. in routing and inventory management.
Our approach is as follows. Section 3.2 discusses the typical determinants of reverse supply chains. Sections 3.3 and 3.4 focus on supply chain strategy. Section 3.5 discusses the qualitative aspects of network design, while Sections 3.6 and 3.7 focus on OR modeling. The chapter ends with the formulation of propositions in Section 3.8.

3.2 The determinants of reverse supply chains

It has often been claimed that the typical characteristics of reverse supply chains justify alternative approaches. Recently, this topic was discussed in the literature by, amongst others, Fleischmann et al. (2000), Fleischmann (2001) and De Brito (2003). This section discusses the typical determinants of reverse supply chains that motivate the development of new reverse supply chain theory.

<u>Business strategy and objectives</u>

Traditional supply chains are focused on the delivery of customer-value against low costs to maximize profits. In reverse supply chains, “soft” objectives like the environment can play a role. The reclamation of value contained in the return is the specific goal of the reverse supply chain. Section 1.2.3 discussed the various individual drivers for companies to handle product returns.

<u>Existing forward supply chain</u>

Reverse supply chains interact with forward supply chains. Therefore, existing forward supply chains are an important determinant of the reverse supply chain. The cost structure of forward supply chains depends on the degree of centralization and mechanization. The costs of the forward supply chain influence the profitability of recovery options and thus the reverse supply chain design. For example, remanufacturing is only worth the effort, if the total costs are lower than the costs of new manufactured products, otherwise another recovery option must be selected. Combining the reverse with the forward supply chain is a potential source for economies of scale, since resources can be shared.

<u>Legislation and social pressure</u>

Legislation and social pressure are factors typically important for closed-loop supply chains. The very existence of some reverse supply chains is based on this pressure. In Section 1.2 we discussed two types of legislation as individual drivers: consumer

rights and environmental legislation. Consumer rights legislation includes warranty and return-and-reimbursement schemes. Environmental legislation in the European Union is based on EPR, making the original manufacturer responsible for proper disposal. The environmental legislation is also complemented by transportation restrictions, processing requirements and export bans for certain discarded products.
Besides legislation, social pressure forces companies to undertake more actions than required for compliance with legislation. A company's reputation and brand name rely on trust and loyalty from customers and thus cannot afford to face public criticism.

<u>The supply side</u>

In most cases, supply in reverse supply chains is a push system, since customers dispose of goods resulting in returns. This contrasts with forward supply chains, which are based on the principle that the customer controls the suppliers: each n-tier supplier is a customer of the (n+1)-tier supplier (Lambert et al., 1998). Although the industry is working on new technology applications to deal with this, reverse supply chains are typically uncontrollable at the supply side, resulting in large inbound stocks to anticipate the uncertainty on three dimensions:

1. <u>Return uncertainty in quantity</u>. The number of products returned from the market is variable. For end-of-use products, estimates on the quantities to be returned are necessary, for e.g. inventory management and remanufacturing planning. In production processes, although quality checks ensure that the production process remains steady and in control, by-products and scrap still occur. The number of warranty returns or repairs for a new product is difficult to predict. The longer the product is on the market, the more empirical data become available, which enables better estimates. In the literature, several techniques have been proposed to reduce uncertainty in quantity by the application of advanced forecast methods, see Toktay (2003) and Toktay et al. (2004).
2. <u>Return uncertainty in timing</u>. The moment at which a single product is returned is mostly unknown. Knowing the composition of the installed base, one can estimate the quantity and timing for groups of products. In some industries, where lease contracts are common business practice, the timing of the return is more or less known beforehand. Some companies apply active buy-back strategies to control or at least influence the timing of product returns. Customers are offered a rebate if they trade-in a machine that does not exceed a certain age (Klausner and Hendrickson, 2000). In addition to policies influencing customer behavior, advanced information and telecommunication equipment can be used to monitor products in the field, see Kokkinaki et al. (2004) and Van Nunen and Zuidwijk (2004). Uncertainty in the timing of end-of-life products increases if the end user stores them before disposal. Many small electrical home appliances, for example,

are relegated to the attic after they lose their usefulness before being really discarded.

3. Return uncertainty in quality and composition. This refers to the condition and composition of the returned product. Reusable items are designed for reuse, and the quality of the product is therefore relatively stable. For warranty returns, the variance in quality is high. A typical phenomenon that increases the variance in quality and quantity of warranty returns is the “non-defective defectives”. Many customers do not understand how to operate a given product or have changed their minds, and then claim that the product did not function properly rather than admit to other motivations (Rogers and Tibben-Lembke, 2001). Preventive measures are taken: CD-roms take customers through a step-by-step process, retailers are trained to investigate returns and call centers also help to prevent returns by providing customer support. If prevention no longer helps, the use of advanced information technology, combined with monitoring, can help to reduce the uncertainty. Electronic data logs on product composition and usage can help to support the inspection and disposition process (Nagel and Meyer, 1999). A major manufacturer of power tools has already implemented an electronic data log for a fast diagnosis of returns on reusability (Klausner and Hendrickson, 2000). A promising concept to reduce uncertainty in composition of returns is the recycling passport, providing the recovery center with precise information (Spengler and Schröter, 2003).

Note that in practice combinations of these three types of uncertainties occur. For example, return uncertainty in variety (product mix) can be seen as a combination of uncertainty in quantity and timing of the individual products.

The demand side

On the demand side, the differences between forward and reverse supply chains seem limited; fulfillment of the demand is the end process in both. Typical characteristics for reverse supply chains are the sometimes less developed markets for “end products”, the existence of parallel markets and obsolescence risk:

1. Development of secondary demand markets. The markets for “end products” of reverse supply chains are not always developed as well as those of forward supply chains. Customers often have a low quality perception, since the product is not new. In closed-loop chains, the market for the recovered product is in many cases internal: remanufactured copiers, refilled printer cartridges or remanufactured single-use cameras. In open-loop chains, it depends on the degree to which the recovered product functions as a substitute or equivalent for new products or virgin materials. For example, the markets for iron scrap and wastepaper are well-developed, since they match the quality of virgin material at

lower cost compared with recycling of e.g. plastics as described by White et al. (2003). The situation for substitute products can even depend on the market segment. In the industrial market, tire retreading, i.e. the remanufacturing of truck tires, is well accepted and cost-efficient, in contrast to the consumer market. Retreading of passenger car tires is currently not profitable because of consumer's negative safety perception, the high collection costs and the competition from budget tires (Debo and Van Wassenhove, 2005). Consumer tires are mainly recovered by material recycling or incineration.

2. Parallel markets. In reverse supply chains, secondary markets sometimes run in parallel or even concur with primary markets. The choice of the market is related to the recovery option, hence of influence on the network design. In the disposition process, multiple recovery options can be selected, resulting in sales on different markets. Tibben-Lembke (2004) reviews the secondary markets for consumer goods. The options widely vary from sell-as-new to recycling or disposal.
3. Obsolescence risk. This refers to the risk of value decay due to changes in the market. The value of fashionable or perishable products quickly diminishes over time. For end-of-life products, the value of the product is already reduced to the intrinsic value of the product and does not change much.

Product characteristics

Reverse supply chains focus on recovery of positive value or neutralization of negative externalities, in contrast to forward supply chains, which aim at value creation. Besides product characteristics that influence the forward supply chain design, products also have several critical dimensions that influence the design of the logistics concept of the reverse supply chain. Here, we focus on these typical reverse supply chain characteristics:

1. Resource value of the product. This refers to the value of the return as a product, in components or in materials. Particularly component or product reuse seem to be beneficial, since much ('forward') added value is preserved, not only materials but also labor and energy, etcetera. Through this so-called "closed-loop effect", returns are reused in their original application (Krikke et al., 2004a), thereby averting the use of "new" resources like energy, materials, labor and machine time.
2. Damage risk. This refers to the risk of safety, environmental or company reputation damage due to returns. Batteries, for example, endanger the environment due to their contamination with heavy metals, i.e. mercury, that can potentially impact groundwater. Another example is the third-party refilling of printer cartridges still labeled with the original brand name (Toffel, 2004). Defects or poorly filled cartridges directly affect the OEM's reputation.

3. DFX and modularization. This refers to the design of the product. DFX (design for X) is defined as an integrated approach to designing products and processes for cost-effective operations from manufacturing through service and disposal (Gungor and Gupta, 1999). It includes design for environment (DFE), design for disassembly (DFD) or design for recycling (DFR) processes. Modularization of products is a typical outcome of product engineering using DFX, and eases the inspection and disposition of the returned product. Reusable items are kept simple to facilitate easy reuse. For complex products, inspection and disassembly must take place to determine the appropriate recovery option. In modularized products, the overall functionality of the product is decomposed in several sub functions, i.e. modules. Modular design allows the grouping of components into easily detachable modules that can be routed and treated differently through the reverse supply chain (Zhang and Gershenson, 2003). Ideally, the economic value of complex products is contained in a few easily separable modules. DFX and modularization influence the design of the reverse supply chain by the location and the way of testing and disassembly.

Reflection: consequences for the network design

As noted, reverse supply chains seem to deal with typical characteristics of a number of aspects: business strategy, objectives, the existing forward supply chain, legislation, social pressure, demand characteristics, supply characteristics and product characteristics. These determinants affect the design of the logistics concept in various ways. Strategy is the first step and depends on the determinants mentioned. The next section elaborates on supply chain strategy in reverse supply chains, the upper part of the logistics concept shown in Figure 3.1. Many studies in the literature skip this essential step and apply the determinants directly to network design. Once we have developed the strategy framework, we discuss the relationship with the determinants. Based on this, we develop the rest of the logistics concept.

3.3 Frameworks for supply chain strategy

The supply chain strategy envisions the supply goals in order to contribute to the overall business strategy. This section first discusses the applicability of the frameworks of Fisher (1997) and Lee (2002) primarily designed for setting the forward supply chain strategy, where the supply chain ranges from raw materials to the consumer. Second, the literature on frameworks for reverse supply chain strategy, particularly Blackburn et al. (2004) and Krikke et al. (2004b), is considered.

The well-known framework of Fisher (1997) distinguishes two product-market combinations based on demand uncertainty and describes the matching (forward) supply chain: an efficient and a responsive supply chain. Lee (2002) extended the framework of Fisher by incorporating uncertainty on the supply side. Lee (2002) distinguishes four types of supply chains; Table 3.1 exhibits the matching type of chain for the various combinations of demand and supply uncertainty:

- <u>Efficient supply chains</u> utilize a strategy to create the highest cost efficiency in the supply chain.
- <u>Risk-hedging supply chains</u> utilize a strategy aimed at pooling and sharing resources in the chain in order to share the risk of disruptions.
- <u>Responsive supply chains</u> utilize a strategy to maximize responsiveness and flexibility in face of changing and diverse needs of their customers.
- <u>Agile supply chains</u> utilize a strategy to maximize responsiveness and flexibility with regards to customer needs, while hedging the risk of supply distortions by pooling inventories and capacity resources.

Table 3.1. Framework for supply chain strategy proposed by Lee (2002).

		Demand uncertainty	
		Low (functional products)	High (innovative products)
Supply uncertainty	Low (stable process)	*Efficient supply chains*	*Responsive supply chains*
	High (evolving process)	*Risk-hedging supply chains*	*Agile supply chains*

In the reverse logistics literature, frameworks that provide principles for determining the reverse supply chain strategy are scarce. Blackburn et al. (2004) propose a framework for commercial returns based on the marginal value of time. Marginal value of time is the degree by which the value of a returned product diminishes over time. This reflects the costs of processing delays as well as the inventory costs of value depreciation due to changed market conditions. Table 3.2 presents this strategy framework for reverse supply chains. Fashion, high-tech or perishable products have a high marginal value of time, in contrast to commodities that take much longer to become dated. Products with a high marginal value of time can best be managed with a responsive reverse supply chain. Responsive chains should assess the return as early as possible, decentralized, and thus differentiate processes as early as possible. This is referred to as the preponement strategy, the opposite of postponement strategies in forward supply chains as for example described by Lee and Tang (1997). Products with a low marginal value of time can best employ an efficient reverse supply chain. Efficient chains are typically centralized to benefit from economies of scale.

Table 3.2. The time-based reverse supply chain strategy framework (based on Blackburn et al., 2004).

	Efficient reverse supply chain	**Responsive reverse supply chain**
Low marginal value of time	Centralized model	
High marginal value of time		Decentralized (preponement) model

Krikke et al. (2004b) propose a framework for determining the reverse supply chain strategy based on the value contained in the return. The value of a returned product is a natural dimension to aggregate the several types of returns, drivers, recovery options and processes. Value must be seen in a broad sense, encompassing material, labor, components, and also brand and corporate image, as discussed in Section 1.2. In principle, value can be driven by the market (customer), by efficiency or by environmental and safety issues. Krikke et al. (2004b) distinguish three types of value for returned products:

- <u>Negative externality value</u>. An externality is an effect resulting from use or disposal of a product that has not been taken into account at an earlier stage. Negative consequences of the decisions taken earlier in the product life cycle need to be managed in order to limit the impact. Hence, potential environmental or safety risks need to be neutralized. Negative influences on company image or brand can also be seen as negative externalities. Moreover, in some cases, legislation can force companies to undertake measures to reduce the negative effects.
- <u>Intrinsic value</u>. Intrinsic value refers to the inherent or built-in value of the returned product. This depends on the type of return. For end-of-use products, the intrinsic value is related to the value in reuse, possibly after some processing. For end-of-life returns, the intrinsic value refers to the material value.
- <u>Time-based value</u>. Time-based value refers to the value of a product return that is highly time-dependent due to technological progress or market processes. This is similar to the marginal value of time of Blackburn et al. (2004).

For each of these types of contained value, a corresponding reverse supply chain strategy can be found. Control reverse supply chains aim at managing and neutralizing negative externalities. The description of the efficient and responsive reverse supply chain in Krikke et al. (2004b) is similar to the description of these chains in Blackburn et al. (2004). Efficient reverse supply chains are used in stable markets and try to obtain economies of scale. Responsive chains are used in settings in which time is critical and processes are thus decentralized. Table 3.3 presents this strategy framework for reverse supply chains.

Table 3.3. The value framework (based on Krikke et al., 2004b).

	Control reverse supply chain	Efficient reverse supply chain	Responsive reverse supply chain
Returns with negative externalities	Environment-, safety- or legislation-driven		
Returns with intrinsic value		Cost-driven	
Returns with time-based value			Market-driven

Reflection: taking the best of both worlds

The supply chain strategy frameworks of Fisher (1997) and Lee (2002) lack certain critical dimensions to be concise in the reverse supply chain area. Their determinants of the supply chain strategy, the demand and the supply side of the supply chain, are exactly two of the distinctions between forward and reverse supply chains. The reverse supply chain should be designed with respect to the phase of the product life cycle, indicating the remaining product value. The reverse supply chain strategy framework of Blackburn et al. (2004) is based on this characteristic and comes to a classification similar to Fisher (1997). Originally, the framework of Blackburn et al. (2004) was designed for commercial returns, but a wider applicability seems feasible. Krikke et al. (2004b) indicate that the value of a return not only is time-dependent, but can also be negative. They add a new type of reverse supply chain, the control chain, to neutralize returns with negative externalities. The framework of Krikke et al. (2004b), however, does not include the time aspect for negative externalities. This is surprising, since some returns have negative externalities that pose an immediate threat and demand swift action, in contrast to other returns where compliance of environmental legislation is important, but not time-critical.

Similar to Fisher (1997) and Lee (2002) we decompose the influence of the determinants on the reverse supply chain strategy. From here we develop the other parts of the logistics concept, i.e. network structure and planning, control and IT. It is captured entirely in two dimensions: value and time.

The differences between forward and reverse supply chains seem to justify the development of a new framework for the reverse supply chain strategy that extends the frameworks known from the literature. This framework should be a structure that provides clear guidelines for determining the reverse supply chain strategy, based on the characteristics of the return. Furthermore, this should be linked to the other elements in the logistics concept: the network design and the planning, control and information infrastructure.

3.4 A new time-value-based framework for strategy

Section 3.3 reviewed the literature and concluded that the current frameworks, while helpful, are not sufficient for determining the reverse supply chain strategy. We propose a framework that combines the value perspective of Krikke et al. (2004b) and the time-dependent perspective of Blackburn et al. (2004).
The framework of Blackburn et al. (2004) shows us that the value of returns can be time related. This seems to hold not only for commercial returns, but also for other types of returns. Every returned product for which technological aging and fashion is critical or which poses an immediate safety or environmental threat, needs a “fast” reverse supply chain. Krikke et al. (2004b) note the time-dependency, but specifically inform us that the value of a returned product can either be positive (due to “forward” resources to be regained) or negative (representing externalities). We propose a framework combining both the value of the returned product (positive – negative) and the time-dependency (low or high). Table 3.4 shows our value – time framework for determining the reverse supply chain strategy.

Table 3.4. The value – time framework for reverse supply chain strategy.

		Value of returned product	
		Negative (negative externalities)	Positive (intrinsic value)
Time-dependency	Low (stable value)	*Control chain*	*Efficient chain*
	High (rapidly diminishing value)	*Protection chain*	*Responsive chain*

A control chain best manages returns that have a negative value and no time-dependency. An efficient chain best handles product returns that have a relative high value and are time-independent. A protection chain is used for handling time-dependent product returns with a negative value. Since the negative externality becomes more threatening with time, protection measures are necessary, e.g. nuclear waste from hospitals or asbestos. Finally, high value, time-critical returns are best managed with a responsive chain, capable of swift action to reclaim value.

These types of reverse supply chains may be summarized as follows:

- Control reverse supply chains have a reverse supply chain strategy aiming at neutralization of negative externalities in an efficient way. Careful registration of input and output processes to verify mass balances is required. Stakeholders typically require reports to verify the responsible processing. Since compliance with legislation is important, legislation is the major determinant of the control chain. The returned products are pushed into the reverse chain. Since quality is relatively stable and time-independent, processes in the chain are steady and focused on efficiency. Market opportunities for the output of the control reverse supply chain are limited.

- Efficient reverse supply chains utilize a strategy aiming at separation of the valuable parts from the returned product in a cost-efficient way. The differences in cost structures between the forward and the reverse chain is the critical determinant in this type of chains. Non-valuable parts can be disposed of, and may enter another chain with a control focus. Since the returned products have a positive value, the chain pulls products from the market / installed base. The secondary market for reclaimed items, whether this concerns spare parts or materials, is stable and relatively easy to find.
- Protection reverse supply chains adopt a strategy aiming at urgent neutralization or management of the negative externality. The negative externality can pose an immediate threat requiring immediate action, not only environmental and safety risks, but also risks to market, assets, brand or company image. These risks refer to value in the broad sense. In contrast to the control type reverse supply chain, time is a critical factor. Damage risk is the critical determinant of the protection chain.
- Responsive reverse supply chains adopt a strategy aiming at responsiveness and flexibility in order to keep throughput times for the returned products in the chain short. Throughput times refer to the time from return from the market to the time the product is put back on the market. Since the value quickly diminishes the most value can be reclaimed with responsive processes. Obsolescence risk is therefore regarded as the critical determinant of the responsive chain.

Table 3.5 summarizes the determinants of Section 3.2 for each strategy. All determinants are captured in two dimensions, value and time, to determine the reverse supply chain strategy.
The remainder of this section describes some representative case examples from the literature for each of the four types, illustrating the use of the framework:

Negative valued, time-independent returns (control chain)

De Koster et al. (2005) describe a collective recycling system of Dutch consumer electronics OEMs/importers. This system is driven by EU legislation based on Extended Producer Responsibility, as laid down in the WEEE directive (Directive 2000/96/EC). Operational processes are outsourced, and the overall deficit is charged to the consumer when buying a new product. The system focuses on carrying out the EU directive, which implies extensive measurements and reporting of material balances. For the processors, large volumes are important in view of cost effectiveness. Collection often proves difficult, since there is a large time gap between sales and return. Products may have changed owners many times and the final user does not have a real economic incentive to hand in the product. Finding markets for the secondary materials also proves difficult. The reverse supply chain is therefore mainly control-driven, minimizing environmental risks and demonstrating compliance with the rules. Similar systems exist for end-of-life vehicles, i.e. the ARN system as described in Chapter 2, for batteries (Schultmann et al, 2003) and for passenger car tires (Debo and Van Wassenhove, 2005).

Positive valued, independent returns (efficient chain)

The steel recycling industry is a typical example of an efficient chain. Scrap metals are valuable and provide a substitute for virgin ore. The markets for scrap metals are stable, except for variations in price resulting from changing market demand. The reverse supply chains for pulp paper and glass show similar characteristics; the reclaimed resources are substitutes for new, markets are stable, and a pursuit of efficiency is needed to make business profitable.

Kroon and Vrijens (1995) describe on a case study concerning small collapsible plastic containers that can be rented. A logistics service provider is responsible for all logistics activities, i.e., storage and maintenance, delivery, and collection of empty containers. Efficiency in operations is needed to make business profitable. A similar situation exists for crates and other packaging materials, for example Matthews (2004), Pappis et al. (2005) and Veenstra (2005).

Negative valued, time-dependent returns (protection chain)

Product recalls for safety reasons are typical for negative valued, time-dependent returns. Moll (2003) describes how the Ford Motor Company had to withdraw more than 14 million tires mounted on the Ford Explorer series in 2000, as a result of serious safety risks caused by tread separations. More than 1400 accidents were linked to these tire problems. Ford limited the damage by replacing the tires as quickly as possible. With the increasing product liability, the importance of product recalls will increase, and one can better be prepared in the supply chain.

Toffel (2004) reports on OEMs protecting the after-sales markets for parts and accessories. OEMs such as Lexmark and Hewlett-Packard see the refilling of original printer cartridges by third-parties as a negative externality, since it may damage their corporate brand and even cause failures resulting in warranty returns of their printers. Since third-parties pull the empty cartridges from the market, the OEMs need to respond quickly to reduce the “leaking”. OEMs are eager to get the original cartridges returned and offer prepaid mailing envelops to customers for returning. Lexmark has even implemented security chips in their printer cartridges and toners that disable printing if these cartridges are refilled by other firms (Toffel, 2004).

Table 3.5. Determinants and strategy focus of the chain types.

	Control	**Efficient**	**Protection**	**Responsive**
Key elements of the business strategy	Legislation compliance, asset protection	Value recovery	Legislation compliance, customer relationship, marketing	Customer relationship, customer legislation, marketing
Importance existing forward supply chain	Low	Medium	High	High
Legislation and social pressure	Medium	Low	High	Medium
Supply side				
Uncertainty in quantity	Low	Low	Medium	Medium
Uncertainty in timing	Low - Medium	Medium	Medium	High
Uncertainty in quality and composition	Low – Medium	Low	Medium - High	Low - Medium
Demand side				
Development of secondary demand markets	Low	High	Medium	High
Parallel markets	Low	Medium	High	High
Obsolescence risk	Low	Low	Low - High	High
Product characteristics				
Resource value	Negative	Positive	Negative - Positive (but externalities)	Positive
Damage risk	Medium	Low	High	Low
Degree of DFX and modularization	Low	Low	Medium	High

Positive valued, time-dependent returns (responsive chain)

Caldwell (1999) describes a case study on Estèe Lauder regarding commercial returns of cosmetics products. Their reverse logistics program involves streamlining of reverse logistics processes including returns authorization, adapting the warehouse management systems and developing reuse markets (company stores). The time-based value of these cosmetics makes responsiveness essential.
Callioni et al. (2005) describe the return of overstocked computers at the resellers in the supply chain of Hewlett-Packard. The value depreciation of a fully assembled computer is estimated at about 1% per week. Similar examples exist in commercial returns in mail ordering and e-commerce, for example Rogers and Tibben-Lembke (1998) and De Koster and Zuidema (2005).

In the examples above, each type of return was classified in one of the four categories. In practice, however, a returned product often possesses a combination of these characteristics. The dominant value-time characteristics must then be used to set the reverse supply chain strategy. In most cases, a network must be decomposed in several chains. Consider, for example, the network for end-of-life vehicle recycling as discussed in Chapter 2. The oils coming from end-of-life vehicles must be drained off within ten working days to prevent ground pollution. Furthermore, the amounts of liquids that are allowed to be stored at a dismantlers' site are restricted by the licenses. Since oil possesses negative externalities, timely action is required, thereby necessitating a protection chain. On the other hand, the vehicle carcass that remains after removal of the ARN materials has a positive material value that requires an efficient chain.

Contribution: reverse supply chain strategy as basis for network design

The framework proposed in this section encompasses all typical reverse logistics determinants in the most natural way. The framework is based on two characteristics of the return: the value and the time-dependency of the value. This is motivated in the description of the four strategies and by the case examples given. The hierarchical nature of the model of Van Goor et al. (1998) suggests that we develop the remainder of the logistics concept from here. The next logical step is to apply this to network design and look for matches with our strategy framework. Section 3.5 uses the literature to distill a network typology for six types of returns.

3.5 Reverse network design typology

This section describes the typical reverse supply chains for the types of returns described in Section 1.3. The literature has described many case studies in the field

of reverse logistics. Several authors have generalized these cases into typologies, e.g. Fleischmann et al. (1997), Bloemhof-Ruwaard et al. (1999), Fleischmann et al. (2000), Krikke et al. (2002), Guide and Van Wassenhove (2002), De Brito (2003), Guide and Van Wassenhove (2003a), De Brito and Dekker (2004) and Krikke et al. (2004). These typologies are valuable in structuring the field and provide a framework to select basic network structures. We distill a conceptual overview from the different typologies. With the use of network design models, i.e. location-allocation models, the actual optimization can be done within the selected concept. This modeling aspect of the network structure is discussed in Section 3.7.
We start the typology with an assessment of the determinants of reverse supply chains as discussed in Section 3.2, for each of the typical returns discussed in Section 1.3. The results are presented in Table 3.6. Each type of return is then matched with a reverse supply chain type. The designs are sketched in Figure 3.2 to Figure 3.7 and summarized in Table 3.7. Furthermore, each type of return is positioned based on the value characteristics in the strategy framework, with the aim to link determinants, strategy and network design.
For each of the reverse supply chain types we provide a brief description.

Rework-recycling network. By-products and production scrap are typically processed in a rework-recycling network. The rework process is either in-line or off-line. In the in-line situation, the product is reworked at the same manufacturing resource, while in the off-line situation an alternative, dedicated resource for rework is used (Flapper et al., 2002). Non-reworkable products are scrapped and recycled to the material level. This type of network differs from the recycling networks, since all processes are internal and return uncertainty is absent. Figure 3.2 depicts the rework-recycling network.

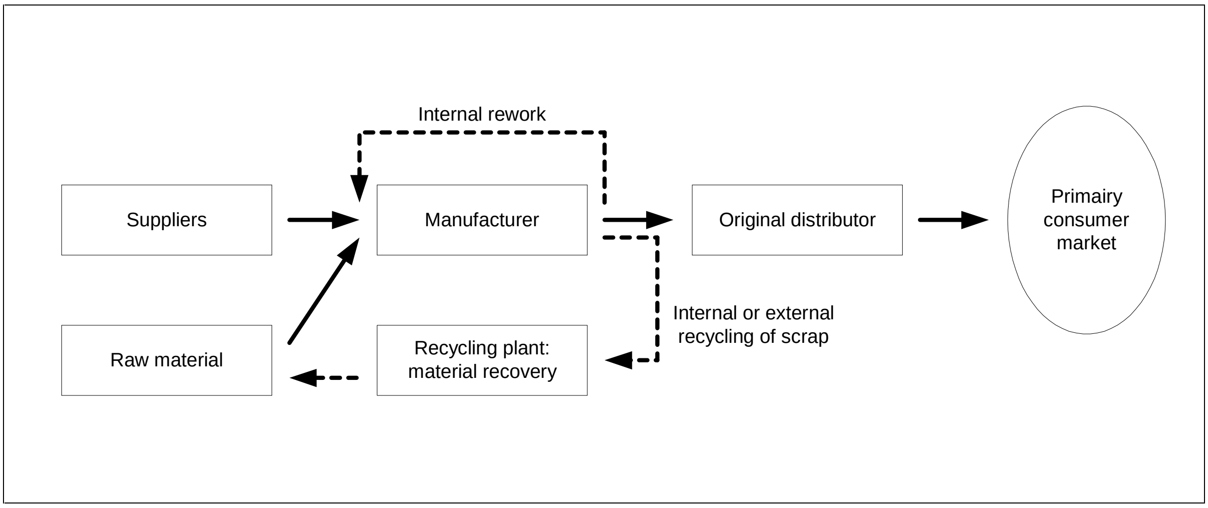

Figure 3.2. Overview of the rework – recycling network for by-products and scrap.

Table 3.6. An assessment of the determinants for each type of return.

		By-products / scrap	Commercial returns	Warranty / repairables / product recalls	Reusable items	End-of-use	End-of-life
Determinants	**Key elements business strategy**	Value recovery / Asset protection	Customer relationship / Consumer legislation	Marketing / Customer relationship / Consumer legislation	Value recovery	Market and asset protection	Environmental legislation / Preemption of legislation
	Importance existing forward supply chain	High	High	High	Medium	Medium	Low
	Legislation and social pressure	Low	Medium - high	Medium - high	Low	Low	High
	Supply side						
	Return uncertainty in quantity	Low	Medium	Medium	Low	Medium	Low
	Return uncertainty in timing	Low	High	Medium	Medium	Medium	Medium
	Return uncertainty in quality	Low	Low	High	Low	High	Medium
	Demand side						
	Development of secondary demand markets	High	Medium	N.A.	High	High	Low
	Number of parallel markets	Low	High	Medium	Low	Medium	Low - Medium
	Obsolescence risk	Low	High	Medium	Low	Medium	Low
	Product characteristics						
	Product value	Medium	High	Medium	High	Medium	Low
	Damage risk	Medium	Medium	High	Low		
	DFX modularization	Medium	Medium - High	High	Low	Medium	Low
From here we develop the supply chain strategy and the network design.							

Table 3.7. For each return type the matching supply chain strategy focus and the matching reverse supply chain.

	By-products / scrap	Commercial returns	Warranty / repairables / product recalls	Reusable items	End-of-use	End-of-life
Supply chain strategy focus	Control - efficiency	Responsive	Protection - responsive	Efficiency	Protection - responsive	Control - efficiency
Matching reverse supply chain	Rework-recycling network	Reverse distribution network	Service-repair network	Exchange network	Hybrid-remanufacturing and trade-repair network	Recycling network
Network characteristics						
Chain director	Manufacturer	Distributor	OEM / LSP	Depot operator	OEM / Independent brokers	OEM / Collective alliances
Acquisition	Internal	Customer return	Customer return	Receiver	Active buy-back / Customer return	Last user return / Disposer
Collection	Internal	Distributor	Distributor	Depot operator / LSP	LSP	Collection points
Disassembly, sorting & disposition	Manufacturer	Distributor	Service office / Reparation center	N.A.	Recovery center	Collection points / Dismantlers
Recovery	Recycling / Remanufacturing	Reuse / Refurbishing / Remanufacturing	Repair / Refurbishing	Reuse (after sorting / cleaning)	Refill / Repair / Refurbish / Remanufacturing	Component reuse / Recycling / Incineration
Redistribution in original or alternative chain	Original	Original / Alternative	Original	Original	Original / Alternative	Alternative

Reverse distribution network. Commercial returns are best managed in a reverse distribution network chain. Products returned from shops due to overstocking, or products returned by customers are typically in good condition. After undergoing inspection in the warehouse, these products can be donated to charity, or sold in personnel stores or on alternative markets using some kind of broker. The high value of the goods makes disposal an unattractive option. Careful selection of the secondary market is necessary in order to prevent cannibalization of sales in the original channel due to competition from discounters, or brand damage due to inferior products in the secondary market. A detailed discussion on aspects involved in the selection of a secondary market for commercial returns is provided by Tibben-Lembke and Rogers (2003) and Tibben-Lembke (2004). Figure 3.3 depicts the reverse distribution network.

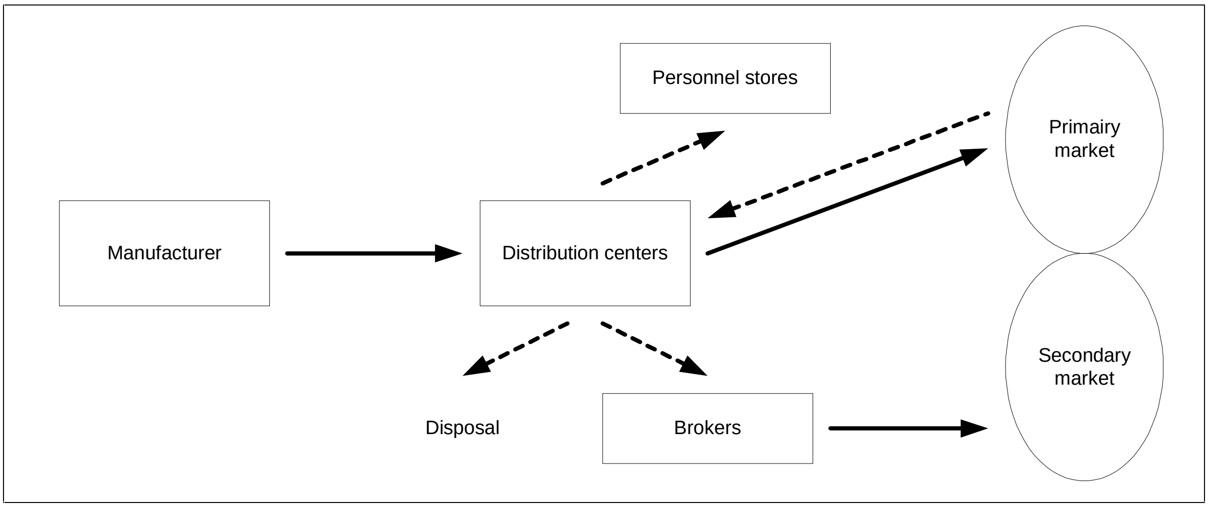

Figure 3.3. Overview of the reverse distribution network.

Service repair network. Warranty returns, repairables and product recalls require a service-repair network. Customers return the product either directly, to the manufacturers service center, or indirectly, using the forward channel entities. In the service center the product is either exchanged, meaning that the product is directly replaced, or returned to the customer after repair. The number of service centers varies depending on the type of product. For cars, the sales and service office coincide with the repair center in a local garage, in a decentralized network. For small and complicated products, requiring special equipment and specific knowledge, service centers are typically centralized on a country, or even continent level. Krikke et al. (2004) described the case of Honeywell, in which service engineers fix defects at the customer side. The suspected components are sent to a central facility for recovery. Figure 3.4 depicts the service-repair network.

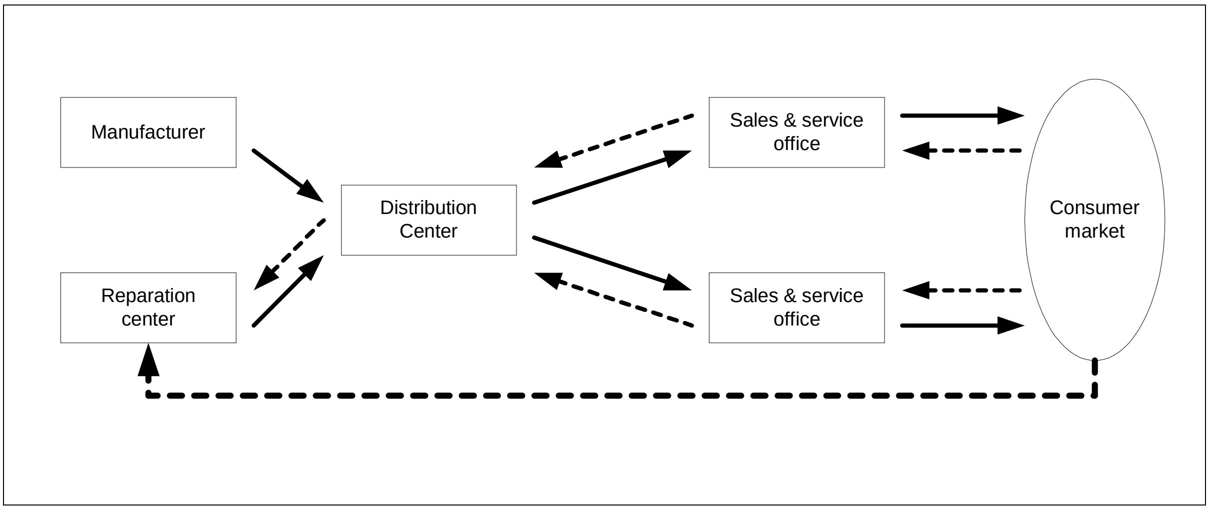

Figure 3.4. Overview of the service – repair network.

Exchange network. Reusable items, typically carriers, are best managed in an exchange system, see for example Kroon and Vrijens (1995) and Matthews (2004). These exchange systems are closed systems, although this is not always obvious due to the large number of users. After receipt of the forward product flow carried by the reusable items, the receiver returns the reusable item either directly to the sender for reuse or to a depot. The depot functions as of an inspection point and a reservoir to store superfluous reusable items. Some systems use deposit money to stimulate the receiver of the reusable item to return it to the system. Figure 3.5 depicts the exchange network for reusable items.

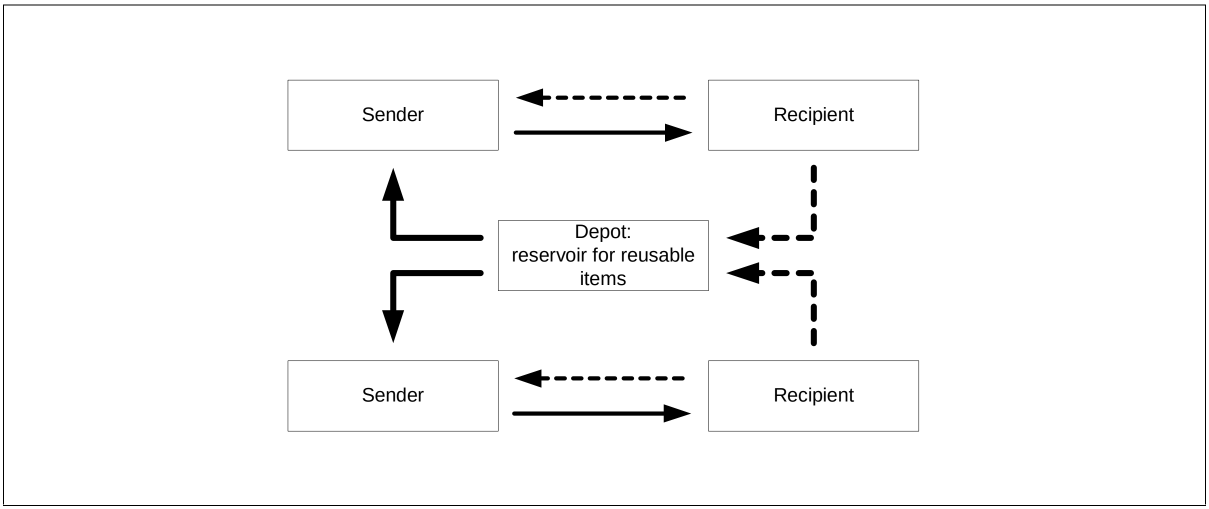

Figure 3.5. Overview of the exchange network for reusable items.

Hybrid (re)manufacturing and trade-repair network. End-of-use returns are processed in a hybrid network that consists of two types of sub-networks: the remanufacturing network and the trade-repair network. The (re)manufacturing network is typical for end-of-use returns reused in the original supply chain, i.e. the closed-loop, for instance with the remanufacturing of copiers as described by Krikke et al. (1999a). Trade-repair networks occur for end-of-use products that are collected from the market by a broker, who send the returned products to third-party recovery center. The products are resold again in the same or in an alternative market. After end-of-use products are tested and dismantled, disposition can take place to either the remanufacturing or the trade-repair network. Printer cartridges are remanufactured by the original equipment manufacturer in a hybrid (re)manufacturing network or collected by independent brokers that refill the cartridges and sell them under a cheap label in a trade-repair network (Toffel, 2004). Similar examples can be given for single-use photo cameras, see Guide and Van Wassenhove (2003a). Figure 3.6 depicts the hybrid (re)manufacturing and trade-repair network.

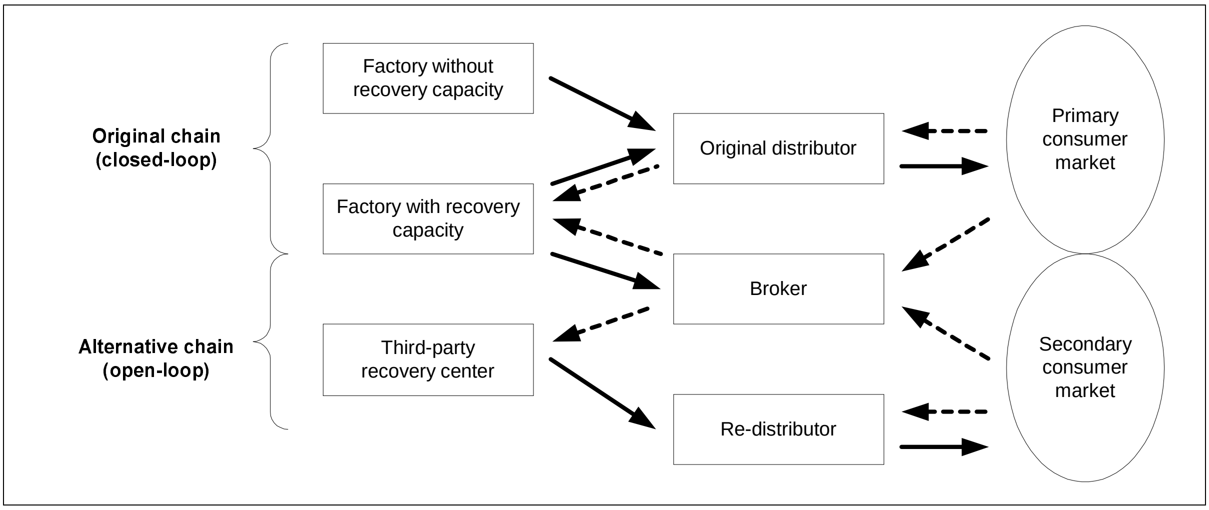

Figure 3.6. Overview of the hybrid (re)manufacturing and trade – repair network.

<u>Recycling network</u>. End-of-life products usually enter a material recycling network. The products are collected and brought to a dismantler for disassembly and disposition. Depending on the degree of centralization, either separate collection points are used to collect discarded products or collection points and dismantlers coincide, as for example described in Chapter 2 regarding the ARN network. After disassembly, the materials of which the product is composed are sent to specialized recycling companies to reclaim the material. The reclaimed materials ideally serve as substitutes for virgin resources, and enter an alternative forward supply chain, i.e. open-loop. Figure 3.7 depicts the recycling network.

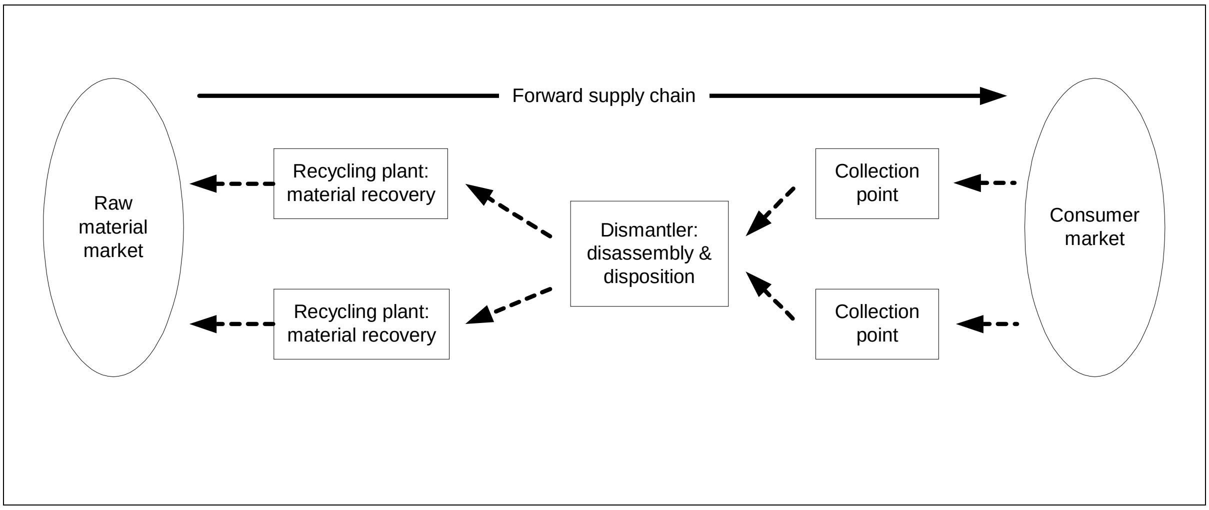

Figure 3.7. Overview of the recycling network.

Reflection: the relationship between determinants, supply chain strategy and network design

Most typologies in the literature evaluate whether or not a reverse supply chain network matches a specific return type. They consider product-market characteristics of the typical returns and select a conceptual network design. Although the typologies are valuable, and help practitioners to select the conceptual model, explicit descriptions of the underlying design principles are absent. Within a strategy one can have multiple types of networks and, the other way around, within a certain type of network one can set different strategies. Consider a recycling network, for example, where the focus can be either on controlling environmental consequences or on obtaining efficiency, when the returned products have value to recover. Figure 3.8 maps the types of return in the strategy framework of Section 3.4. This mapping shows that the causal relation between the type of return, the determinants and the network design must be questioned. The basis for the reverse supply chain strategy is provided in Table 3.4. An analysis on how to translate a chosen strategy in a certain network design is needed. The case studies of Chapters 4, 5 and 6 serve to this end.

Since our focus is on network structure design and its consequences for operations research, we analyze the planning, control and IT layer of the logistics concept as far as it is relevant to network design. A large part of the thesis discusses the OR modeling consequences. Therefore, the next section introduces a framework of reverse supply chain planning processes.

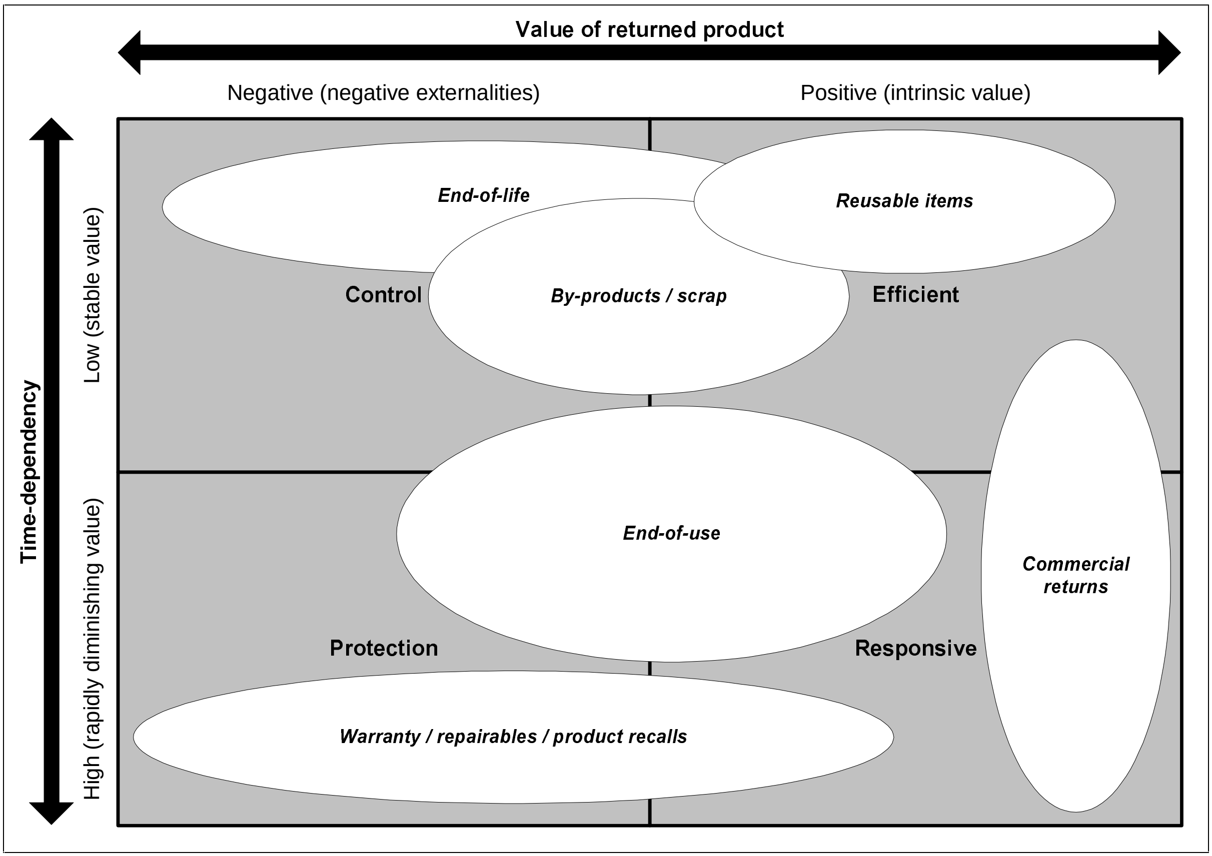

Figure 3.8. The types of returns in the reverse supply chain strategy framework.

3.6 Reverse supply chain modeling

This section positions the models and techniques used in this thesis within the field of operations research for reverse supply chains. Since we present the supply chain planning matrix for both forward supply chains and reverse supply chains, their differences in this area can be mapped straightforwardly.

Only a few decades ago, planning processes were the domain of planners with well-developed analytical skills who manually worked out detailed plans. In the late 1980s, Enterprise Resource Planning (ERP) systems emerged and became a major technology to manage transactions within the supply chain (Stadler and Kilger, 2002). Implementation of ERP systems often did not meet expectations, although visibility and opportunities for information exchange improved, and unity in the data source was obtained (Shapiro, 2001). There was support for planning and scheduling in these ERP systems was limited. Geoffion and Krishnan (2001) stated: firms found essentially no P in ERP.

Planning is the preparation for making decisions (Fleischmann et al., 2002). Control is the inspection of the consequences of the decisions taken. The number of decisions taken in all levels of the supply chain, from the strategic level via the tactical level to the operational level, is enormous. The value of information technology to support planning and control is evident. This has resulted in the introduction of APS (Advanced Planning and Scheduling) modules that complement the ERP systems. APS modules use operations research models to support decision making in planning processes. Stadler and Kilger (2002) describe in detail give the current state of APS. An overview of APS modules in the supply chain planning matrix of Meyr et al. (2002) is given in Figure 3.9.

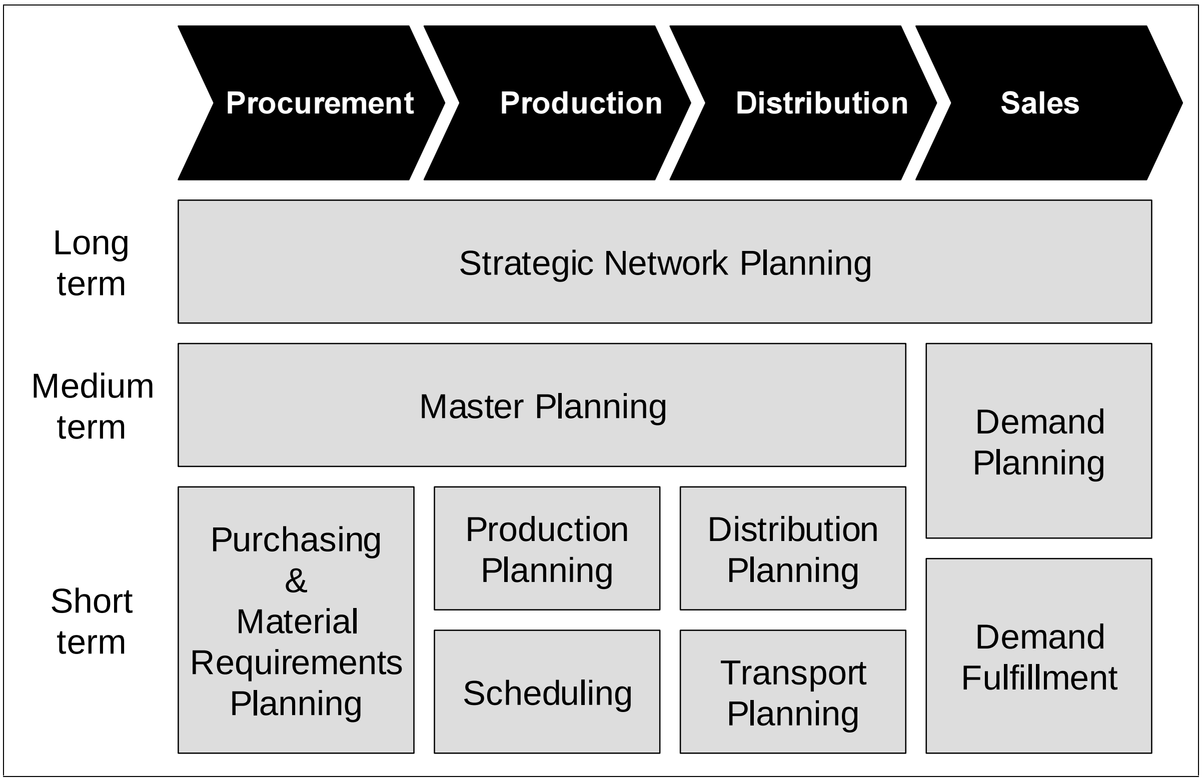

Figure 3.9. Supply chain planning matrix (adapted from Meyr et al., 2002).

The literature on OR models for reverse logistics has developed strongly in recent years. Many of the papers are case-based, discussing some forms of industrial remanufacturing. Fleischmann et al. (1997) provide an overview of the use of mathematical models in network design, inventory management and production planning and control. Gungor and Gupta (1999) take a broader perspective by discussing the literature on environmentally conscious manufacturing and product recovery. Also the books edited by Guide and Van Wassenhove (2003) and Dekker et al. (2004) contain chapters dedicated to planning and control as well as supporting information technology.

Decision support techniques from operations research can be used to improve the planning processes. This thesis uses OR models to perform case studies in strategic network planning. The required detail sometimes compels us to analyze operational processes, but the scope remains on the tactical or strategic level. In the remainder

of this thesis, we will restrict ourselves to studying network planning and its interaction with collection or reverse distribution planning.
The remainder of this section discusses our supply chain planning matrix for reverse supply chains, which resembles that of Meyr et al. (2002). Following the product over the life cycle we focus on planning processes in the reverse logistics phase; in other words: after distribution, sales and installed base management, but before manufacturing with reuse. Figure 3.10 depicts our reverse supply chain planning matrix.

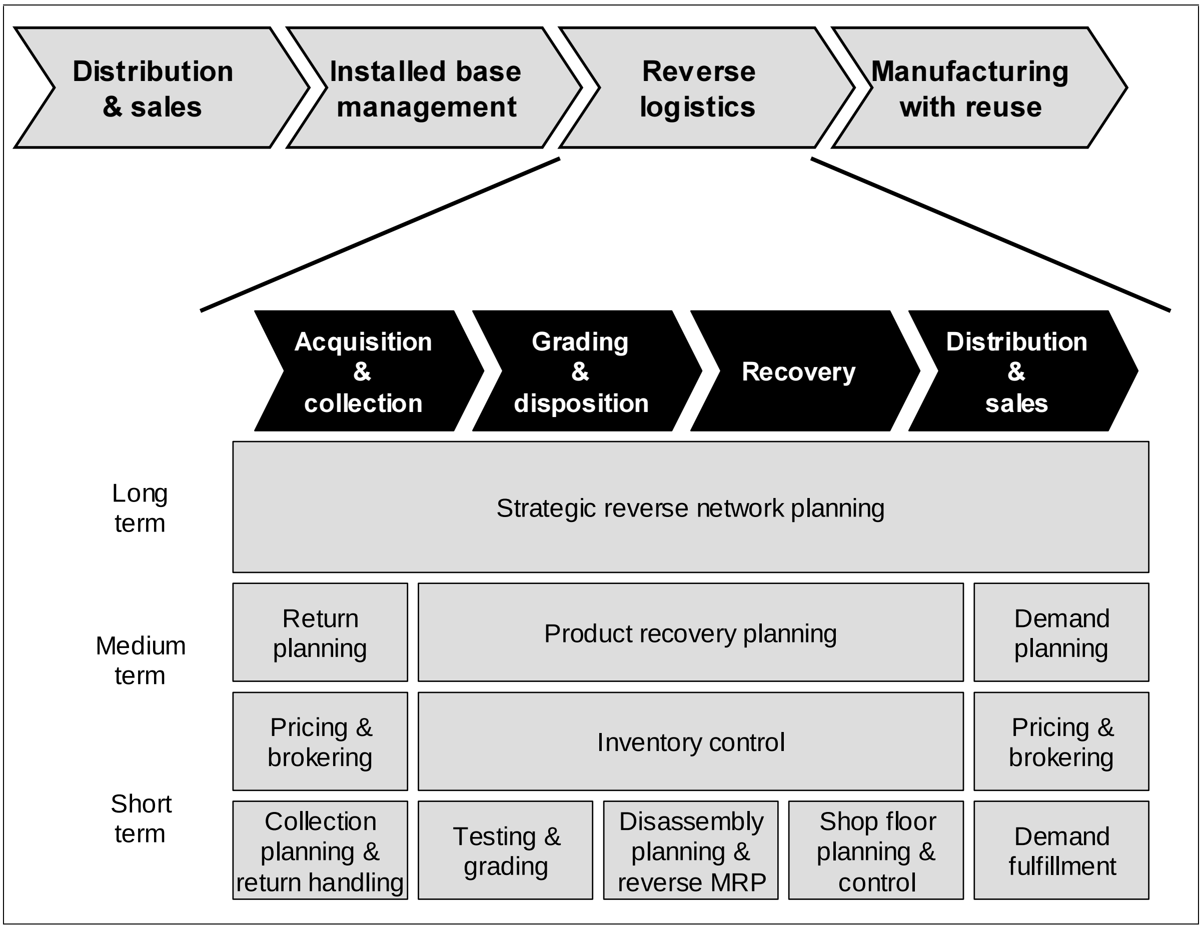

Figure 3.10. Reverse supply chain planning matrix.

<u>Strategic reverse network planning</u>

Strategic reverse network planning is typically a top-level management task involving the upper part of the pyramid of the logistics concept, as sketched in Figure 3.1. It includes the processes of designing the collection or reverse distribution network, planning the location and the capacities of the recovery facilities, and allocating the recovered products to the markets. Section 3.8 elaborates on strategic network modeling and discusses the importance of, and interaction with, other operational planning processes, in particular routing.

Return planning

Return planning is the acquisition of data on the types and amounts of products in the installed based that can be returned. The goal of this process is to obtain data necessary for better decision-making. This involves the use of not only forecasting models, but also Delphi-like methods for incorporating human judgment. The literature in this area is limited. Goh and Varaprasad (1986) and Kelle and Silver (1989) describe methodologies for the planning of reusable container returns. Toktay (2003) and Toktay et al. (2004) provide an overview of forecasting techniques for return planning. Similar to Wagner (2002) in demand planning in forward supply chains, three dimensions can be distinguished: a product dimension, a geographic dimension and a time dimension. The product dimension includes information on the product group, family or line, and on the condition or quality of the returned products. The geographic and the time dimensions refer to the region and the time instant of the released returns. This information is of direct importance for collection and for planning the required capacities for facilities.
Acquisition decisions are sometimes incorporated in the recovery planning process (Spengler et al., 2003), which provides support regarding the decision to accept a batch of returns for recovery and in the fee to be charged or price to be offered.

Pricing and brokering

Pricing and brokering occurs on both the supply and the demand side of the reverse supply chain.
On the supply side, pricing and brokering is the process of organizing the acquisition of returns from the market. The pricing and brokering process, together with the return planning, is also referred to as product acquisition management. Product acquisition management is the interface between collection activities and the value recovery operations in the reverse supply chain. An overview of product acquisition management appears in Guide and Jayaraman (2000). Here, we restrict pricing and brokering to the management of stimuli for customers to return the product, i.e. products acquisition. For some products, acquisition is difficult: consumers with little incentive to return a product must be encouraged by economic stimuli, which may take the form of a reward or a trade-in rebate. Furthermore, not only pricing plays a role, but also ease of returning. For example, simple administrative procedures, such as providing prepaid mailing envelopes or specially designed boxes, enhance return rates. Guide et al. (2003a) propose an economic model to determine the acquisition price for cores, depending on certain predefined quality classes.
On the demand side, pricing and brokering comprises the process of managing the secondary demand channels and matching the demand for recovered products with the available supply. In closed-loop chains, the process is internal and includes the negotiation of transfer pricing between two profits centers. In open-loop situations,

electronic marketplaces as described by Kokkinaki at al. (2000) and Krikke et al. (2004b) and brokers as described by Rogers and Tibben-Lembke (1998) play a role in supporting price setting. Brokers usually do not handle the product themselves, but provide the service as intermediaries between the market and the reverse supply chain. In a similar way, e-marketplaces and brokers also support the processes on the supply side of the reverse supply chain.

Collection planning and return handling

Collection planning and return handling are the processes of organizing and planning the transportation of returns and the handling of the received goods. The case of transportation with the possibility of consolidation to obtain economies of scale is discussed extensively in forward logistics, referring to vehicle dispatching or vehicle routing models. Beullens (2001) and Beullens et al. (2004) provide an extensive overview on collection and vehicle routing aspects in reverse logistics. Special vehicle routing models have been developed that allow the combination of forward and reverse flows in the same vehicle. The resulting models include vehicle routing models with backhauling (Goetschalckx and Jacobs-Blecha, 1989), vehicle routing models with simultaneous pick-up and delivery (Dethloff, 2001), and the pick-up and delivery model (Dumas et al., 1991). In situations where a regular schedule with predetermined visit frequencies is appropriate, for example in the collection of waste from as described by Angelelli and Speranza (2002) and Teixeira et al. (2004), periodic vehicle routing models are used. Sectorization of customers is frequently applied in order to balance workloads (Beullens, 2001). Combining forward and reverse orders in vehicles complicates not only the routing problem, but also the loading problem. Simple first-in-first-out policies for loading do not suffice when pick-ups and deliveries are mixed.

Returns transported to a facility must be unloaded and handled before further processing can take place. De Brito and De Koster (2004) discuss issues in return handling. Return handling involves the process of receipt, internal transportation and storage. Depending on the type of return, return handling is directly related to grading and disposition, commercial returns, for instance, with direct reuse as a recovery option. Research in this area is limited and in most cases is referred to standard literature on handling forward flows.

Product recovery planning

Product recovery planning is concerned with the selection of recovery options on a tactical level. Recovery options for the returned products are determined by the following: process capacities, available inventory, the supply of returns, market demand and prices. Decisions coming from the strategic network planning processes are the starting point in this medium-term refinery process, although adaptations of strategic models can sometimes be applied. The model of Krikke et al. (2003) selects the recovery process based on economic, technical and environmental criteria, once the facilities are fixed beforehand. Thierry (1997) describes a model for optimizing both forward and return flows given the locations and capacities for facilities. This model considers tradeoffs with respect to new manufacturing, remanufacturing and disposal. Spengler et al. (1997) develop a model for determining the type of dismantling and linking it to the type of recovery option. Their results are based on a real-life case study in the dismantling and recycling of domestic buildings. Beullens (2001) develops a cost-benefit model for matching supply and demand in a network such that revenues are maximized. Significant variance in demand, supply and prices occur in situations with material recycling (particularly metals), and reconsidering such a model on regular basis seems advisable. This is also observed by Spengler et al. (2003), who describe an integrated model for the daily planning and acquisition of cores for the recovery process, and present an application in electronics recycling. The model maximizes profit by selecting the way of disassembly and determining the recovery options.

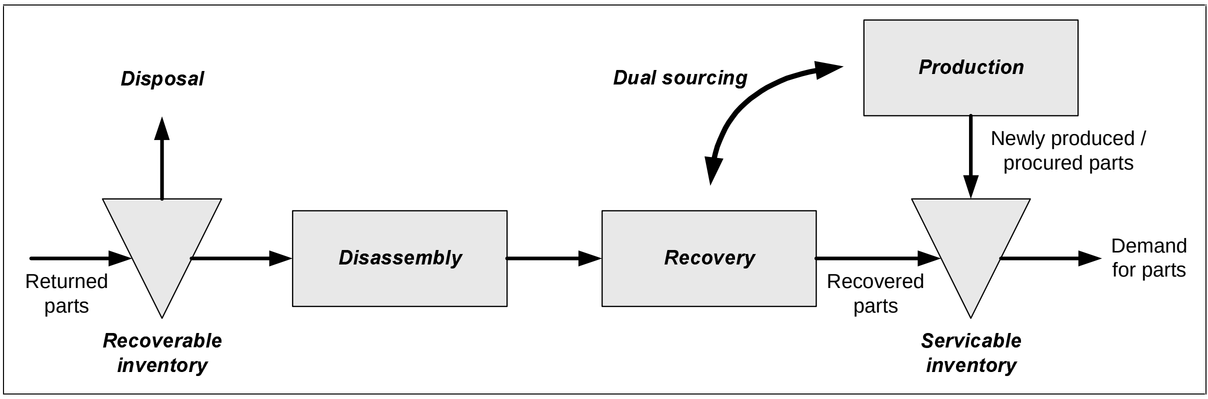

Figure 3.11. Two types of inventories in product recovery systems.

Inventory control

Inventory systems are discussed by many authors, see for example Van der Laan et al. (1999), Toktay et al. (2000) and Fleischmann (2001). Although this discussion here refers to inventory control of parts, similar concepts apply to materials, sub-assemblies or products. Inventory planning systems with returns introduce the option of dual sourcing; one can either use newly procured or manufactured parts or employ recovered parts. Figure 3.11 sketches this situation. Another decision variable is added in cases where parts in the recoverable inventory can be disposed of, because the capacity of physical inventory is limited, and costs are incurred for the recoverable inventory. These additional decision variables, combined with the uncertainty in timing, quantity and quality of returned products complicate inventory planning. Inventory management in reverse logistics therefore differs greatly from traditional models in forward logistics (Van der Laan et al., 2004).

The inventory planning models in reverse supply chains can be classified as either deterministic or stochastic. The deterministic models handle lotsizing decisions, where orders are processed in batches to obtain economies of scale. For a detailed discussion on these types of models, see Minner and Lindner (2004). Stochastic inventory systems include those with either autonomous or managed recovery, for an overview see Van der Laan et al. (2004). In the autonomous situation, i.e. push policy, available cores are immediately taken from recoverable inventory and are stored in the serviceable inventory together with new parts waiting for demand. In the managed or pull situation, returns are stored in the recoverable inventory, and are recovered on demand. Since orders are processed in batches, the excess of recovered parts is stored in a serviceable inventory together with newly procured or manufactured parts.

<u>Testing and grading</u>

The literature on testing and grading is rather scarce. Although well-documented case studies provide us with insights in current business practice, a structured research framework is missing. Krikke et al. (1999a) describe the classification of returned copiers into four quality classes. Guide et al. (2003) describe the grading of cellular phones. Klausner and Hendrickson (2000) describe the application of electronic logs in power tools enabling easy grading of returned machines based on parameters stored in the log. In the ARN system discussed in Chapter 2, the ELV-dismantling company estimates the quality of the parts. Some ELV-dismantlers even grade the dismantled parts into quality classes, offering different degrees of warranty to the customers.

Testing and grading is a process that currently relies on the experience of practitioners. The use of advanced technology, as advocated by Van Nunen and Zuidwijk (2004), creates knowledge bases to formalize the decision logic. We expect this development to continue and even to be extended with the application of decision support models. For example, Geyer et al. (2005) describe a case in which a repair center also collects and analyzes failure information for process improvement purposes.

<u>Disassembly planning and reverse MRP</u>

Disassembly planning receives a lot of attention in the literature, due to its relevance in various recovery systems. In almost all situations, parts of the product need some processing, whether replacement, repair, cleaning, etc. and therefore need to be disassembled. Although disassembly can be considered as the counterpart of assembly, it is more complex. The degree of disassembly, i.e. to which extent the product should be disassembled to keep profitability and environmental impact at a desired level (Gungor and Gupta, 1999), and the sequence of disassembly are the main decision variables. For example, Krikke et al. (1999b) describes a case study in determining the optimal degree of disassembly and assigning the recovery option based on a profit criterion. The decisions even take into account the state of the product that is revealed during the disassembly process. Disassembly planning concerns the appropriate design and organization of the disassembly process (Inderfurth et al., 2004), and covers not only the manner of disassembly and its depth, but also sequencing decisions, i.e. in which order to remove parts from the original product. Since non-destructive disassembly operations are labor intensive, in contrast to destructive disassembly (e.g. shredding), there is some pressure for optimization. A detailed literature review on disassembly sequencing is provided by Lambert (2003).

Disassembly planning is related to reverse material requirements planning (reverse MRP). MRP is a standard methodology for production planning that transforms the demand for a certain product into a schedule of requirements at the level of components and raw materials. Reverse MRP decomposes a returned product into a set of components and materials demanded for the subsequent recovery process (Gungor and Gupta, 1999). The high degree of uncertainty in reverse supply chains requires adaptation for the reverse MRP approach, i.e. setting of safety stocks. Thierry (1997) compares different MRP approaches in a remanufacturing environment with their behavior under uncertainty. He concluded that the dual-bill of material method, using both an assembly and a disassembly bill-of-materials, performs best, especially in situations where remanufacturing is economically attractive. A weakness of all MRP methodologies is the neglect of capacity limitations. To overcome this, Guide et al. (1997a) discuss methodologies for rough-cut capacity planning in remanufacturing systems. In this process, the recovery plan is transferred into capacity requirements for key resources.

Shop floor planning and control

Shop floor planning and control is the day-to-day task of capacity planning and scheduling in order to avoid bottlenecks and promote high productivity. The individual processing requirements, and thus variable shop floor routing of returned products, complicates processes. This is particularly relevant for remanufacturing and refurbishing situations. In situations where a low-grade recovery option is selected (e.g. recycling), the process can be considered as continuous and variants of classical models apply. Guide et al. (1997) examine disassembly release mechanisms and priority rules in a remanufacturing environment in order to control work centers workloads. Kizilkaya and Gupta (1998) propose a kanban system for controlling the disassembly of products into parts that are used for new product assembly. Voutsinas and Pappis (2002) discuss scheduling in a remanufacturing environment, where the value of the released components quickly diminishes.

Inderfurth et al. (2004) describe the present state of research. Overall, the literature on shop floor planning and control in reverse supply chains is limited. Almost all of the cases described in literature almost all refer to a remanufacturing situation.

Demand planning

Demand planning is the acquisition of data on the types and amounts of products demanded by customers, a process similar to the one in forward supply chains (Wagner, 2002). The goal of this process is to obtain data necessary for better decision-making, e.g. product recovery planning. This process can be seen as the counterpart of return planning. Forecasting techniques are used to support demand planning. For closed-loop supply chains, the demand is internal. In many cases, an alternative sourcing option exists to cope with demand exceeding the number of recovered parts or products. In open-loop supply chains, this depends on whether or not the market is well-developed. With regard to scrap metals, for example, the demand planning process is merely a market monitor with which to observe demand, supply and prices. In under-developed markets, it is also the process of finding new opportunities to use the recovered parts or materials. In the ARN system, for example, safety belts coming from ELVs are used as tree belts or as shoulder straps for trendy bags. The remaining safety belts are recycled as synthetic fleece.

Demand planning in closed-loop supply chains is often related directly to return planning, since demand can be satisfied effectively using recovered products. To the best of our knowledge, demand planning without a direct relation with return planning is not discussed in the literature. An overview of demand planning in forward supply chain management is given by Wagner (2002).

Demand fulfillment

Demand fulfillment is the process of ensuring that actual demand is satisfied. In forward supply chains, it is traditionally the search for inventory to quote against orders or against production (Kilger and Schneeweiss, 2002). The goal is to meet the demand requirements with the available supply of recovered products. In closed-loop supply chains, demand fulfillment is internal within the chain, and sometimes even within the same facility. For open-loop supply chains, demand fulfillment is concerned with preparing customer orders for distribution and providing the customer with the necessary information; this has strong similarities with forward supply chains. Demand fulfillment is also concerned with newly occurring customer demand. Based on inventory positions and planned processes, the available-to-promise (ATP) amount is known. An overview of demand fulfillment processes is given by Kilger and Schneeweiss (2002).

Contribution

This section developed a reverse supply chain planning matrix analogous to the supply chain planning matrix of Meyr et al. (2002). This matrix provides a framework within which to position decision support models based on two dimensions: the planning scope and the nature of the process. For each of the processes we describe the type of planning problem and refer to the relevant literature.

In our opinion, the literature on planning processes, and the modeling aspects in particular, is unbalanced: some areas are over-represented, while others are almost absent. This is also reflected in the limited attention of software houses to advanced planning modules to support planning processes in reverse supply chains (Van Hillegersberg et al., 2001). There is a gap to bridge. However it is important to realize that, while in some areas new operations research models may be needed, in others standard models may suffice.

This thesis focuses on the upper part of the matrix in Figure 3.10: strategic network planning. We focus on network design and its interactions with operational planning processes, in particular routing.

3.7 Modeling reverse logistics network design

This section examines strategic network planning. Strategic network planning, located in the upper part of the supply chain planning matrix, is the modeling of network design. Optimization techniques for designing supply chains have been widely applied since the 1970s (Geoffion and Powers, 1995), and the literature in this field is abundant. This section focuses on the modeling of reverse supply chain networks.

3.7.1 Literature review on location – allocation models

In our opinion, reverse supply chains are essentially different from forward supply chains in a number of aspects, which are the so-called determinants, as discussed in Section 3.2:

- Business strategy
- Existing forward supply chain: chain and cost structures
- Legislation and social pressure
- Supply characteristics:
    - Return uncertainty in quantity
    - Return uncertainty in timing
    - Return uncertainty in quality and composition

- Demand characteristics:
  - Development of secondary demand markets
  - Parallel markets
  - Obsolescence risk
- Product characteristics:
  - Resource value of the product
  - Damage risk
  - DFX and modularization

In previous sections, we argued that reverse supply chain network design, as part of the full logistics concept, should be based on a reverse supply chain strategy. This reverse supply chain strategy, in turn, relies on the value-time framework described in Table 3.4, which is able to cope with all determinants. It seems questionable, however, whether the determinants justify new models. This paragraph examines the location-allocation decisions in the reverse supply chain that determine the physical layout of the network. Since location-allocation decisions are discussed extensively in both the forward and reverse supply chain literature, we restrict this overview to the latter. Overviews of applications of mathematical models in reverse logistics network design can be found in Fleischmann et al. (2000), Fleischmann (2001), Krikke et al. (2003) and Fleischmann et al. (2004). Table 3.8 provides an overview of reverse network design models found in the literature, together with their main characteristics and their classification in the analogy of Krikke et al. (2003). These characteristics are the application, open- or closed-loop, the objective function, the scope of modeling, type of decisions and type of model. What we notice is the following.

Mixed-integer programming is the most frequently applied technique for models supporting location - allocation decisions. In some cases, the locations are fixed, and the model reduces to an allocation model that can be solved by simple linear programming, see Ossenbruggen and Ossenbruggen (1992), Bloemhof-Ruwaard et al. (1996a) and Thierry (1997). Louwers et al. (1999) provide an exception, using a continuous location model, which results in a non-linear programming model that is solved to optimality using standard software.

Most models discussed in the literature are deterministic; the uncertainty aspects that make reverse supply chains different from forward chains are not dealt with model-wise. Attention to network design models that explicitly consider uncertainty is limited; most authors suffice with deterministic models with extensive sensitivity analysis. Realff et al. (2004) extend the mixed-integer linear programming model of Realff et al. (1999) to a robust optimization framework, taking into account several scenarios in the mathematical optimization. Listes and Dekker (2005) develop a stochastic model for reverse network design, extending the work of Barros et al. (1998). Their results are promising, but issues concerning the robustness and the long running times should be solved, see also Listes (2002).

A number of models consider the design of both the forward and the reverse supply chain. Fleischmann (2001) investigates the effects of simultaneous and sequential design of the forward and the reverse supply chains in two cases: copier remanufacturing and paper recycling. He concludes that simultaneous design is recommended if the return rate is high and there are major differences in the cost structure between the forward and the reverse supply chains. Existing forward supply chains do not constitute a barrier for setting up reverse supply chains (Fleischmann, 2001). Even in the success cases, in practice, where the reverse supply chains directly serve as input for the original forward supply chain, the degree to which design decisions are taken integrally seems limited.

In the literature, cost minimization prevails over profit maximization, probably since the demand and prices for recovered products are assumed to be exogenous. Most models neglect the environmental impact, rather than incorporating environmental aspects of transportation and processing in the analysis. Exceptions are Caruso et al. (1993), Bloemhof-Ruwaard et al. (1996a) and Krikke et al. (2003), which adopt multi-criteria models to optimize simultaneously the cost/profits and the environmental impact.

So far, the models applied for reverse logistics network design seem to differ little from the models in forward supply chain design. Mixed-integer programming methods are dominant in forward supply chains, as can be seen in the review of Vidal and Goetschalckx (1997). Geoffrion and Powers (1995) describe supply chain design aspects from evolutionary processes, where, besides the technical aspects, developments in software and hardware play a critical role. An overview of general facility location models is presented by Hesse Owen and Daskin (1998), and more recently by Klose and Drexl (2004). With the growing importance of globalization, a recent development in the supply chain design literature is the research on global supply chain models. Global supply chain models incorporate trading aspects, currency exchange rate risks and differences in taxes and duties, see for examples Arntzen et al. (1995) and Vidal and Goetschalckx (2001). Linking the issues in this field to reverse supply chain designs seems interesting since, even within the European Union, border crossing with return flows is often a serious issue.

Table 3.8. Reverse network design models in the literature.

Authors (literature reference)	Application	Closed/open-loop	Specification model			
			Objective	Scope	Decisions	Type
Barros et al. (1998)	Sand recycling	Open	Cost min.	Reverse	Location-allocation	MILP
Beamon and Fernandes (2004)	Electronics remanufacturing	Closed	Cost min.	Forward and reverse	Location-allocation	MILP
Berger and Debaillie (1997)	Computer remanufacturing	Closed	Cost min.	Reverse	Location-allocation	MILP
Bloemhof-Ruwaard et al. (1996)	Fictitious case by-products	Open	Cost min.	Forward and reverse	Location-allocation	MILP
Bloemhof-Ruwaard et al. (1996a)	Paper	Closed	Environment impact min.	Forward and reverse	Allocation	LP
Caruso et al. (1993)	Solid waste	Open	Multi-objective	Reverse	Location-allocation	MILP
Fleischmann (2001)	Paper and copiers	Closed / Open	Cost min.	Forward and reverse	Location-allocation	MILP
Gottinger (1988)	Solid waste	Open	Cost min.	Reverse	Location-allocation	MILP
Jayaraman et al. (1999)	Electronics remanufacturing	Closed	Cost min.	Reverse	Location-allocation	MILP
Krikke et al. (1999a)	Copiers remanufacturing	Closed	Cost min.	Reverse	Location-allocation	MILP
Krikke et al. (1999)	Fictitious case	Open	Cost min.	Reverse	Location-allocation	MILP
Krikke et al. (2003)	Refrigerators recycling	Closed	Multi-objective	Forward and reverse	Location-allocation	MILP
Kroon and Vrijens (1995)	Reusable transport packages	Closed	Cost min.	Forward and reverse	Location-allocation	MILP
Louwers et al. (1999)	Carpet recycling	Open	Cost min.	Reverse	Location-allocation	NLP
Marin and Pelegrin (1998)	Fictitious case	Closed	Cost min.	Forward and reverse	Location-allocation	MILP
Ossenbruggen and Ossenbruggen (1992)	Solid waste	Open	Cost min.	Reverse	Allocation	LP
Püchert et al. (1996)	End-of-life vehicle recycling	Open	Cost min.	Reverse	Location-allocation	MILP
Pugh (1993)	Solid waste	Open	Cost min.	Reverse	Allocation	LP
Realff et al. (1999)	Carpet recycling	Open	Profit max.	Reverse	Location-allocation	MILP
Shih (2001)	White and brown goods recycling	Open	Profit max.	Reverse	Location-allocation	MILP
Schultmann et al. (2003)	Battery recycling	Open	Cost min.	Reverse	Location-allocation	MILP
Spengler et al. (1997)	Industrial by-products from steel industry	Open	Cost min.	Reverse	Location-allocation	MILP
Thierry (1997)	Fictitious case	Closed	Cost min.	Forward and reverse	Allocation	LP

3.7.2 The impact of routing on supply chain design

The location – allocation models of the previous section take decisions based on cost parameters assumed to be known beforehand. This seems questionable, especially for transportation costs. The classical assumption for estimating transportation costs is that distribution or collection tours consist of a single customer (Salhi and Rand, 1989). Transportation costs, however are largely determined by economies of scale (Fleischmann, 1993). These synergies can be estimated only by using detailed models expressing the possible synergies in combining customers in a distribution or collection tour. Some authors have proposed so-called location-routing models for determining the layout of the network, taking vehicle routing aspects into account.

Our interpretation of (reverse) supply chain design is somewhat broader than the physical network layout, and involves interactions with operational processes; in particular chain orchestration decisions on inventory and routing. Consider, for example, the application of innovative logistics concepts for distribution, such as vendor managed inventory (VMI) and factory gate pricing (FGP). In 2003 we investigated the supply chains of grocery retailers under factory gate pricing (Le Blanc et al., 2004b). FGP concerns the transition from delivery of goods to the DC of the customer by the supplier to collection of goods by the customer at the factory gates of the supplier. Factory gate pricing is sometimes also referred to as ex-works pricing. Transportation costs are a major determinant of the total supply chain costs; exchanging information on transportation costs and adapting the control structures can lead to cost reductions of up to 27%.

Our experience in forward supply chains indicates that, beside the physical network structure, orchestration decisions on the strategic level are critical elements of supply chain design. We also emphasize the importance of transportations costs in network design, while the literature pays limited attention to them. These costs are included in the classical location-allocation models, however, the estimation of the transportation costs is often not dealt with explicitly, or are based simply on distance, ignoring synergy effects. Especially in end-of-life product recovery networks, where the value of returns is limited and collection takes place in a geographically dispersed area, transportation costs account for a large fraction of the total costs. We therefore state that special attention to transportation costs in reverse supply chain design is necessary.

Reflection

The often-mentioned special determinants of reverse supply chains do not seem to have a great impact on the modeling of reverse supply chain networks. This literature survey allows us to conclude that standard modeling techniques for location-allocation decisions from forward supply chains fit adequately in the reverse supply

chain setting. The differences between forward and reverse supply chains in the network design modeling seem to be diminishing, as reverse supply chains are becoming a standard supply chain element (Fleischmann et al., 2000). This vision is supported by the limited differences in the models applied in forward and reverse supply chains. Mixed integer programming is dominant. Typical reverse supply chain characteristics are either ignored or deemed irrelevant for the network design phase. Small adaptations of the models seem to be sufficient to cope with reverse supply chain design. In our view, it is more important to take an integral approach to the reverse logistics concept. As part of this, we investigate the interaction between location-allocation and routing (transportation planning) as an example of an orchestration decision in reverse supply chain network design. The attention paid to transportation cost estimation in reverse supply chain design is limited, although it is likely to be an important factor, similar to forward supply chains, as we saw in the factory gate pricing example.
Case studies in the subsequent chapters refer to situations in which the physical network structure is (re)designed. The required level of detail forces us to incorporate routing aspects in the analysis. Although routing is an operational process, we discuss applications of routing for strategic and tactical purposes.

3.8 Propositions

In Chapter 1, we defined closed-loop supply chain management as the integration of business processes that create additional value for all original and new players in the supply chain by closing the goods flows. A cycle is created, starting with manufacturing (possibly with reuse), sales and distribution processes, service logistics or installed base management, and via reverse logistics back to manufacturing with reuse. More specifically, it means extending the forward supply chain with a reverse supply chain to handle returned products. In this thesis we study the design of this reverse supply chain. Based on the literature and theory on closed-loop supply chains discussed in this chapter, we formulate three propositions, each of which highlights one of the key issues as formulated in the research questions in Section 1.5. In Chapter 7, we return to these propositions for refinement, based on the case studies. Our ultimate aim is to develop general design principles for reverse supply chains, which we validate for the domain defined in Section 1.6.

3.8.1 Determining the reverse supply chain strategy

Strategy setting is often neglected in the design of reverse supply chains. The literature on reverse supply chain design takes the typical determinants of returns as a starting point for network design. Section 3.3 reviewed the literature on both forward and reverse supply chain strategy frameworks. None of the existing frameworks seems to capture all of the determinants of the reverse supply chain strategy. In Section 3.4 we therefore introduced our own framework. Key dimensions for determining the strategy are the value contained in the returned product and the time-dependency of this value. Note that “product” also includes components, packages, carriers, refillable units and so on. We characterized the corresponding reverse supply chains as control, efficiency, protection or responsiveness focused. We formalize this principle in proposition 1.

Proposition 1
The closed-loop supply chain strategy can be based entirely on the value of the returned product and the time-dependency of that value. This captures the impact of all the considered determinants. The network design logically follows from the strategy. The matching reverse supply chain is either efficient, responsive, control or protection focused.

3.8.2 Network design and the interaction with the other elements of the logistics concept

This thesis considers the interaction with operational planning processes to be important, as motivated in Section 3.7.2. In general, closed-loop supply chains concern closing loops in goods, information and markets. The design of these chains should therefore cover the full logistics concept from strategy and network design to planning, control and information infrastructure. Currently, the literature on reverse supply chain design neglects the interaction between network design and operational planning processes, e.g. chain orchestration decisions in routing and inventory management. Proposition 2 reflects this discussion.

Proposition 2
A reverse supply chain should deal integrally with the full logistics concept; the current reverse supply chain design literature is too much concerned with its single elements. Reverse network design exceeds location - allocation and should be based on the reverse supply chain strategy and interact with the lower level elements of the logistics concept.

3.8.3 Network design and the modeling consequences

Section 3.6 discussed the forward and the reverse supply chain planning matrix. The question is whether we need different models and techniques in the network design process. In proposition 2 we state that network design is more than location – allocation in both forward and reverse supply chains. It is also concerned with the interaction with other elements of the logistics concept, i.e. operational planning processes. Nevertheless, the literature offers no proof that the special determinants of reverse supply chains justify the development of new methodologies in the field of reverse network design. We formalize this viewpoint on modeling reverse supply chain network design in proposition 3.

Proposition 3
The specific reverse supply chain determinants do not lead to special reverse supply chain design problems from an operations research point of view. Therefore, the development of special operations research models or algorithms for reverse supply chain network design is not justified.

3.8.4 Outlook to the business cases

Each of the next three chapters of this thesis describes a different case study. These cases are situated within the network of Auto Recycling Nederland, as described in Chapter 2. The methodological criteria for case selection are discussed in Chapter 1. For ARN, the cases were selected based on the following:

- Practical relevance; i.e., the case concerns problems currently faced by ARN.
- Consistency with long-term prospects; i.e., the case fits or is part of ARN's strategic transition towards a system with an emphasis on post-shredder separation techniques (PST) instead of manual dismantling in order to reduce costs and raise the recycling target.

In Chapter 7 we return to the propositions for reflection and refinement, based on the case experiences in Chapters 4, 5 and 6. We aim at refining the design principles for reverse supply chains in general, and for situations comparable with ARN, more specifically. As motivated in Section 1.6, ARN is considered to be a representative case for end-of-life management in a collective solution, executing extended producer responsibility. This means that, on the one hand, we are improving the quality of the design principles by validating them in this specific context in end-of-life return returns. On the other hand, the scope of the propositions is reduced to this context.
The relationship between the propositions, the logistics concept and the theory in this chapter is illustrated in Figure 3.12.

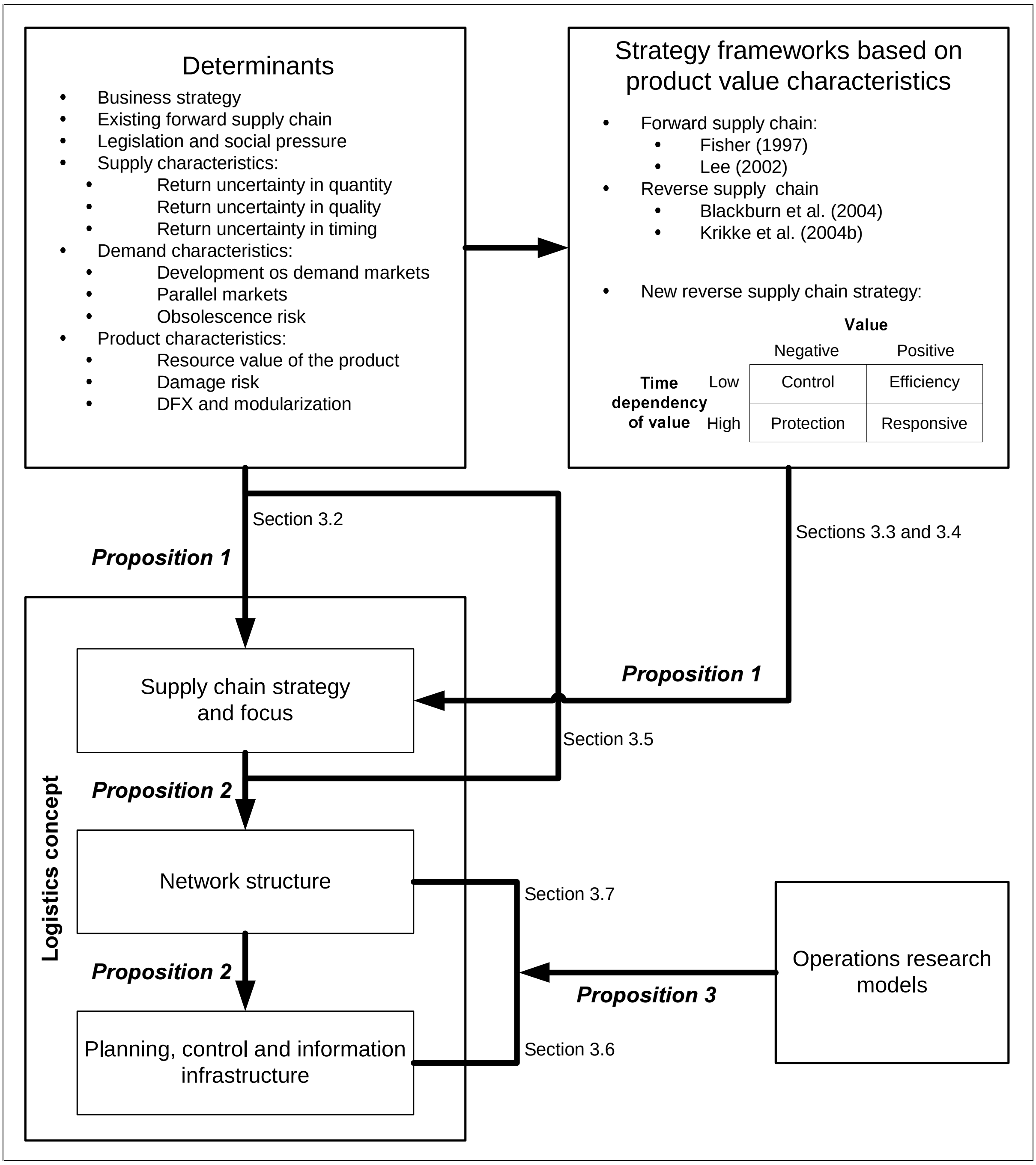

Figure 3.12. The relation between the propositions.

Chapter 4

Case study: redesign of a recycling system for LPG-tanks

"Recht is iets kroms dat verbogen is en daar heb ik verstand van als zakenman zijnde."
Bul Super (3082)

The content of this chapter was published in revised form in OR Spectrum (Le Blanc et al., 2004).

This chapter describes a case study performed in 2001-2002 for Auto Recycling Nederland, dealing with the trade-off between secondary trade (business) and material recycling (environmental safety). It discusses a redesign of the LPG-tank (Liquefied Petrol Gas) recycling network such that economic trading can prevail in an environmentally responsible way. We concentrate in this chapter on the case description. Reflection to the theory, and especially the propositions of Chapter 3, is presented in Chapter 7.

This chapter is built up as follows. Section 4.1 describes the problem and the current system, for which we present the proposed alternatives in Section 4.2. Section 4.3 links our research to the literature. Section 4.4 discusses the methodology, while the analysis results appear in Section 4.5. Finally, the case study is concluded in Section 4.6.

4.1 Problem description

Although the ARN system is generally considered a success, there have been some concerns about the recycling of LPG-tanks, which are one of the 19 separate materials to be recovered from the ELV before shredding. Particularly in the coming years, LPG-tanks will be a main issue for end-of-life vehicle recycling in the Netherlands. The improvement of diesel engines has diminished the popularity of LPG as fuel, effectuating in a current market share of about 1.6% for new cars sold. The market share under cars with an age between 5-9 years is about 5.4%. When an ELV is discarded, the LPG-tank has to be degassed, because the remaining gas in the tank can turn the ELV into a small bomb. This degassing is obligatory before reuse or material recovery can take place. During the degassing process, the tank is put under pressure, so that the gas can escape through a valve, which is connected to a storage tank. This process guarantees that the LPG-tank is absolutely safe and contains no traces of gas.

The Netherlands has only one degassing facility for LPG-tanks, which has been part of the ARN-system since 1999. ELV-dismantlers can store dismantled LPG-tanks in a rack with a capacity of 12 tanks, which are collected on call if the rack contains at least 10 LPG-tanks. Note that when the term “collection” is used in this chapter, we refer to transportation to an intermediate facility, rather than the more general reverse logistics term “collection” as defined in Chapter 1. The collected LPG-tanks are brought to the degassing facility. The regained gas is reused as fuel; the bad LPG-tanks are scrapped, while the good tanks are traded in the second-hand market by the degassing company. Degassed tanks are thus not returned to ELV-dismantlers. ELV-dismantlers have, however, discovered this market. The lucrative trade opportunities for LPG-tanks cause the ELV-dismantlers to not submit their LPG-tanks for degassing. Instead, they sell the used tanks, still filled with gas, right away on the market, thereby causing a high safety risk. As a result, only a small fraction of the LPG-tanks is actually degassed and recycled through the ARN-system. Data available from the Dutch vehicle register make it possible to determine how many LPG-tanks should be degassed. In 2002, 12,853 vehicles with LPG-tanks signed off in the register for dismantling by ARN-affiliated ELV-dismantlers, while only 6,897 LPG-tanks were submitted for degassing; the results for 2000 and 2001 were even worse. Although there is some time delay in this registration (not all deregistered vehicles are dismantled immediately), this cannot explain the entire gap. Moreover, this effect should smoothen out over the years. This means that a large portion of the LPG-tanks is traded without degassing, which is likely to result in environmentally hazardous recycling.

ARN, as executor of the extended producer responsibility, is liable for the proper treatment of ELVs. ARN is therefore eager to solve this problem by making the system more attractive for ELV-dismantlers. In the new system, the degassed tanks should be returned to the dismantlers so that they can trade the tanks themselves. The lucrative business for ELV-dismantlers is to be sustained, while safety can be guaranteed, and the degassing company is compensated for the higher costs. In order to implement such a system, a few alternative systems have been worked out. Our OR-based analysis will show that solutions can be found that are both safe and economically sound.

4.2 The proposed alternative systems

As mentioned, the new system should guarantee the return of degassed LPG-tanks to ELV-dismantlers. A critical issue is the lead time between degassing and return: if it becomes too long, there is a risk that ELV-dismantlers will not use the degassing service and simply continue trading non-degassed LPG-tanks. The idea is therefore to use a fixed frequency transportation system: ELV-dismantlers are visited periodically, where in every period a rack with non-degassed LPG-tanks is exchanged for the rack with degassed LPG-tanks from the previous period. A period of 3 or 4 weeks is considered to be acceptable by ARN management.

In the current situation the storage racks each have a capacity of 12 LPG-tanks. A typical ELV-dismantler should process more than 2,000 wrecks per year for an acceptable fill-rate of the storage rack, which is not realistic. An underutilization of storage racks and trucks will therefore occur when a fixed interval is introduced. A smaller rack with only 6 storage positions might help to improve the efficiency of the operations. Other sizes are not applicable and ARN will only use one type of storage rack, because of handling purposes.

Clearly, a periodic system is expected to result in transports with a relatively low fill-rate; one would like to consider, therefore, whether it would be possible to have a mobile degassing facility outfitted on a small truck. An engineering company worked out this concept and with use of a slightly different degassing technique, it proved feasible.

Combining the above, two basic strategies are considered:

- Central strategy. LPG-tanks are transported periodically from the ELV-dismantlers and to the current central degassing facility. After degassing, the LPG-tanks are returned. Degassing takes place at one location.
- Regional strategy. LPG-tanks are transported to a number of depots located in the Netherlands that are periodically visited by the mobile degassing facility to degas the LPG-tanks. After degassing, the LPG-tanks are returned. Degassing takes place at a limited number of locations.

In the central strategy, the degassing location is known, namely the current degassing facility. For the regional strategy, the number of depots and their geographic location need to be determined. Originally, a third alternative strategy was considered, where every ELV-dismantler was visited periodically by the mobile degassing facility. This option, however, soon turned out to be unfeasible, because the Dutch government would not grant licenses for LPG-tank degassing at every ELV-dismantler site.

Summarizing, the following questions posed by ARN management need analysis:

- What is the best strategy (central or regional); if it is the regional strategy, what is the optimal number of depots and their geographic location?
- What are the effects on costs of a 3- or 4-week periodic system?
- What are the effects on costs of a storage rack with 6 or 12 positions?

4.3 Literature and the chosen approach

4.3.1 Related models and techniques in the literature

Section 3.8 of Chapter 3 provided an extensive review of the network design models in reverse logistics, the majority of which are location-allocation models using mixed-integer linear programming. Sensitivity analysis was used to analyze the impacts of changes in parameters due to the uncertainty inherent in reverse logistics. Attention for stochastic models for reverse supply chain design is limited, although the recent work of Listes and Dekker (2005) is promising. These stochastic models are limited mainly by the extensive data requirements and long running times.
The case study at hand deals with not only a location-allocation problem, but also a routing problem. Accurate transportation cost estimations are required to express the subtle changes in the scenarios, especially in transportation frequency and the size of the storage racks. A combination of location, allocation and routing decisions is known in the literature as location-routing problems. Min et al. (1998) provide a survey of the literature in this area. The practical possibilities of these models are still limited because of computational difficulties. As stated by Lin et al. (2002), there is a need for effective computational approaches for solving location-routing problems of realistic size. Min et al. (1998) come to a similar conclusion when stating that the practical application by logistics professionals is waiting for an algorithmic breakthrough.

4.3.2 Positioning our approach in the literature

The problem size limits the applicability of both stochastic models and location-routing models. Ideally, we would have combined both approaches in a stochastic location-routing model, such as the one described in Laporte et al. (1989). However, our research deals with a real-life case study considering over 250 nodes in the network, which is too large for both types of models. We therefore conclude that both stochastic models and location-routing models are not suitable, and adopt another approach based on classical techniques.

This case study uses a standard location-allocation model, formulated as an integer linear program (IP). Unlike the uncertainty in the number of LPG-tanks to be collected in every period, the uncertainty regarding the number and timing of storage racks to be collected is limited, due to the introduction of fixed collection intervals.

Important inputs for the location-allocation model are good estimations for the transportation costs to the different depots, which are not available at ARN. Location-allocation models assume that the transportation costs are known, usually based on shipment volume and distance. In the case at hand, we need more detailed data on transportation costs to express the differences between the different scenarios. By modeling the operational transportation activities as a (separate) vehicle routing problem, we are able to make reliable estimations for strategic purposes. This approach is similar to that of Schultmann et al. (2004), who used the same combination of models.

We incorporated the special characteristics of this planning problem in the integer programming and vehicle routing model, which are discussed in the next section.

4.4 Methodology

Our methodology consists of three steps, as is shown in Figure 4.1. In the first step, parameters are initialized based on the scenario and the strategy selected. Second, a vehicle routing model is used for estimating the transportation costs for each candidate location to the ELV-dismantlers. Third, an optimization model is performed to optimize allocation and to determine the optimal number of depots and, in case of the regional strategy, their geographic location.

4.4.1 Initialization

During the initialization phase, the length of the collection period and the size of the storage racks are fixed. A collection period is defined as the time between two consecutive visits of the truck for collection and return of storage racks. Although the yearly number of LPG-tanks that should be collected at each ELV-dismantler is relatively stable, the number of storage racks needed and hence to be collected strongly depends on the choice of a collection period and the size of a storage rack. These parameters, which are calculated during the initialization phase, are crucial input for the remainder of the models.

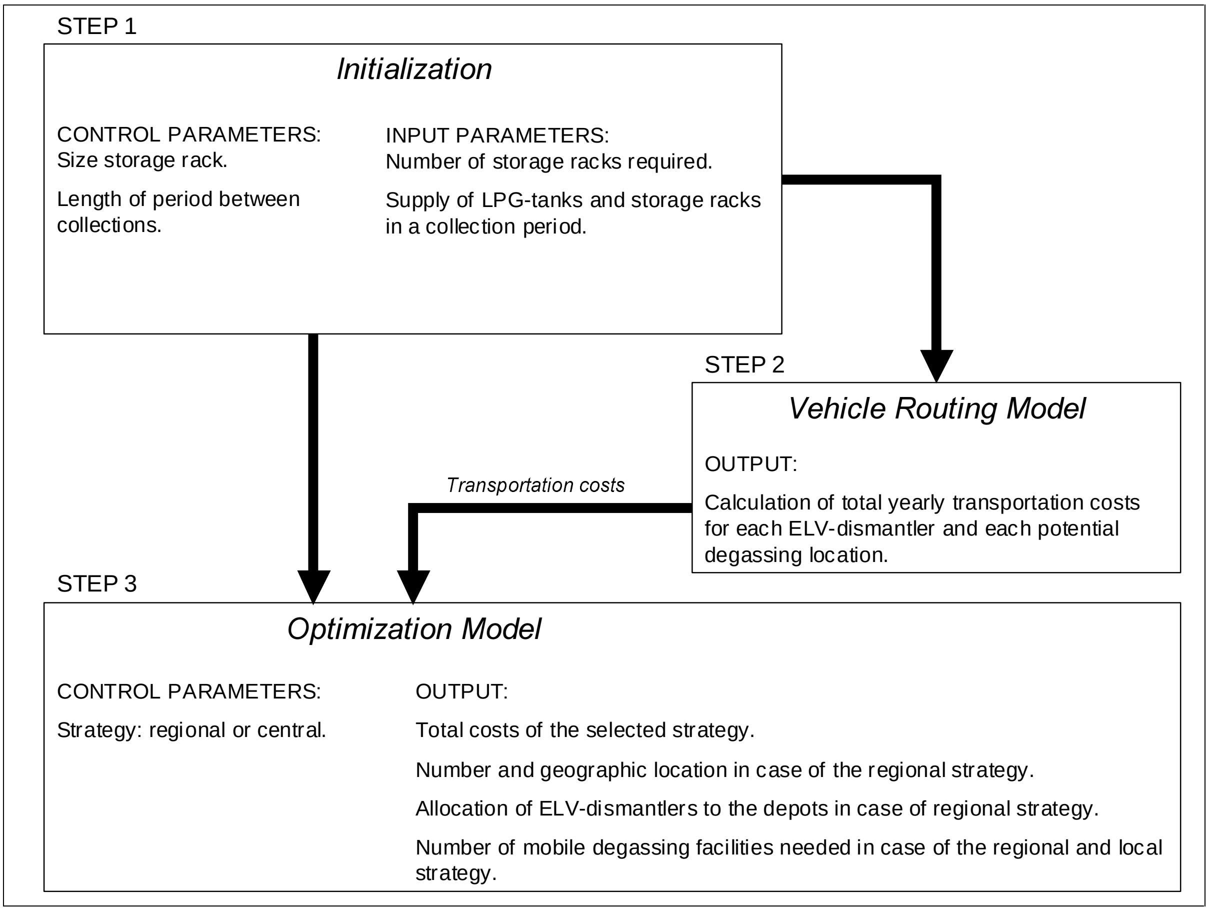

Figure 4.1. The three-step methodology. The basic calculations (initialization) and vehicle routing model serve as input to the optimization model.

4.4.2 Vehicle routing model

A vehicle routing model determines the cheapest routing of trucks, visiting given locations for delivery and pick-up, taking into account time and capacity restrictions. In mathematical terms: consider a complete undirected graph G = (V, E), where the set V consists of one depot and a number of ELV-dismantlers. The set of edges E consists of the connections between the locations. Traveling along an edge e incurs certain costs c_e and travel time t_e. The goal is now to find a set of routes starting and ending at the depot, visiting all the ELV-dismantlers at minimal costs such that the maximal workday length T and the vehicle capacity C are not exceeded. This is a standard vehicle routing problem. The problem at hand, however, is a pick-up and delivery situation that seems to be quite common in reverse logistics, see Beullens (2001) and Dethloff (2001).

In total, there are 30 locations to which an ELV-dismantler can be allocated for tank degassing. We applied this vehicle routing model for all combinations in order to estimate the transportation costs accurately. In total, 30 vehicle routing models are solved, because the vertex set V consists of only one depot at a time. Each time the vehicle routing model is solved, we have a set of routes in which all ELV-dismantlers are visited from the same depot. Together with the costs of the routes, we make estimations of the costs of visiting a particular ELV-dismantler. For allocation in the IP model, the problem is to assign the costs of the routing to the ELV-dismantlers visited in that route. Our research took a simplified approach by allocating the costs linearly with the time the truck was physically at an ELV-dismantler location. Time at locations is calculated as the sum of administrative time (fixed for all ELV-dismantlers) and the loading and unloading time; this depends, in turn, on the number of storage racks and comes from the parameter initialization for the selected scenario.

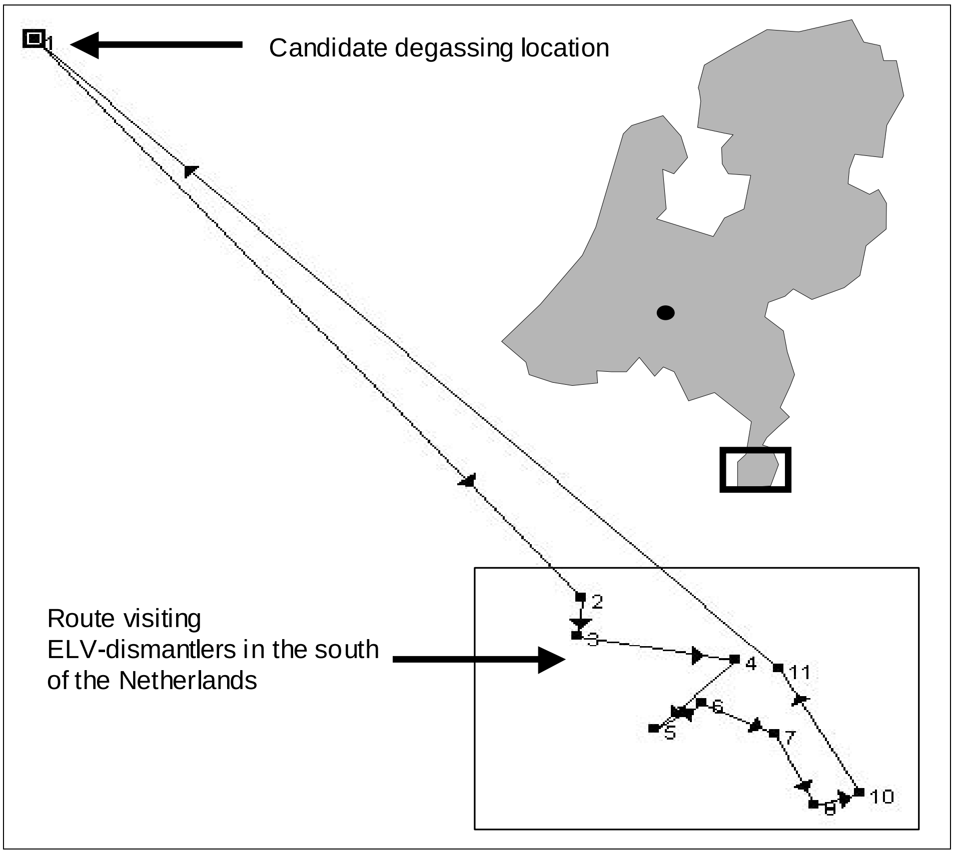

Figure 4.2. An example of a route in the south of the Netherlands.

We argue that this method of allocation is reasonably fair, if all the ELV-dismantlers in a route are located in the same region. This can be assumed to be accurate, for the following reasons. A truck drives to a region, visits ELV-dismantlers in this region and drives back. Figure 4.2 provides an example of such a route. Because of the periodic visiting of all ELV-dismantlers every three or four weeks, routes are fixed and not dynamic. Moreover, after optimization of the routes, all ELV dismantlers within this region are found to be part of the same route; this renders the time-based cost allocation justifiable. Recall that the application of the vehicle routing model results in estimations of the allocation costs for each ELV-dismantler to each degassing location in the location-allocation model: using the distance between the ELV-dismantler and the degassing location as a cost allocation measure is not fair, because it does not express the synergy advantages of multiple visits in a route.

The complexity of the vehicle routing problem is such that it is not solvable to optimality in a reasonable amount of time. However, the number of storage racks to be picked up is the same as the number of storage racks to be delivered per location making it a standard vehicle routing problem. We can therefore combine some basic heuristics described in the literature, see for example Van Breedam (2001). We first apply the nearest neighbor heuristic for finding a starting solution and then use local search techniques for improvement of the initial solution. The local-search procedure consists of making swaps of customers in the different routes, considering capacity and working time restrictions. Theoretically, the application of more advanced heuristics might result in lower costs solutions and therefore lower cost estimations. Instead of pursuing an optimal solution, however, we aim for a realistic one that resembles ARN practice.

4.4.3 Optimization model

For the reverse logistic network redesign for LPG-tanks we use a location-allocation cost minimization model with some additional constraints, concerning the mobile degassing facility capacity and the location(s) allowed in the selected strategy. All parameters in the model depend on the selected strategy and scenario. As soon as the user selects a strategy and scenario, the appropriate values of the parameters are calculated and initialized. A strategy is defined by the choice for either central or regional degassing. A scenario is defined by choices regarding the length of the collection period and the size of the storage racks.

The following decision variables are included:

- Binary variable indicating whether or not location loc is selected: Y_{loc}.
- Binary variable indicating whether or not ELV-dismantler ed is allocated to location loc: $X_{ed,loc}$.
- Integer variable representing the number of mobile degassing facilities needed: #MOBILE.

The set ED with index ed refers to the set of all ELV-dismantlers, and the set LOC with index loc refers to the set of all potential degassing locations, both central and regional candidates.

Assignment of an ELV-dismantler to a certain location incurs certain costs. The model minimizes the total of the following cost components constituting the total yearly costs of the system under consideration:

- Yearly degassing costs per tank ($degascosttank_{loc}$): mobile degassing uses another technology, which incurs variable costs per LPG-tank are incurred. The number of LPG-tanks at each ELV-dismantler is given by the parameter $\#tank_{ed}$.

- Yearly degassing costs per storage rack ($degascostrack_{loc}$): the location at which degassing takes place determines the ease of handling of storage racks and therefore the variable degassing costs per storage rack. The number of storage racks at each ELV-dismantler is given by the parameter $\#rack_{ed}$.
- Yearly collection costs ($colcost_{ed,loc}$): the costs for collecting and returning the racks with LPG-tanks: this is the parameter estimated by the vehicle routing model multiplied by the number of collection periods in a year.
- Yearly storage costs of a storage rack for LPG-tanks at a location ($storcost_{loc}$).
- Yearly depot costs ($depotcost_{loc}$): the fixed costs for selecting a certain depot for degassing, including the yearly depreciation and interest costs of the investments needed for adapting the location for LPG-tank degassing and other fixed costs that are independent of the number of storage racks and LPG tanks. The central degassing facility is also considered as a depot involving fixed operating costs.
- Yearly costs of a set of storage racks (deprerackcost): this includes the yearly depreciation on investment, interest costs and maintenance costs, which all vary with the size. The number of racks needed varies with the length of the collection period and the size of the storage racks.
- The yearly costs of a mobile degassing installation (mobilecost): this includes yearly depreciation on the investment, interest, insurance, maintenance and personal costs.

Combined with the decision variables this results in the objective function [4.1].

$$\begin{aligned}
\text{Min} & \sum_{ed \in ED} \sum_{loc \in LOC} \big(\#\,tank_{ed} \cdot degascosttank_{loc} \\
& + \#\,rack_{ed} \cdot degascostrack_{loc} \big) \cdot X_{ed,loc} \\
& + \sum_{ed \in ED} \sum_{loc \in LOC} \big(colcost_{ed,loc} + \#\,rack_{ed} \cdot storcost_{loc} \big) \cdot X_{ed,loc} \\
& + \sum_{loc \in LOC} depotcost_{loc} \cdot Y_{loc} \\
& + 2 \cdot deprerackcost + mobilecost \cdot \#MOBILE
\end{aligned} \qquad [4.1]$$

The number of racks is determined per scenario as a function of collection frequency, demand and rack capacity. The set of feasible locations is given per strategy, and is adjusted in the initialization of the location set. Each unique strategy-scenario combination is optimized and compared. Per strategy and per scenario we minimize the objective function [4.1] of the model. For the sake of easy comparison, the costs of the storage racks for the different scenarios are included in the model; this does not influence the optimization procedure, however. Note that two sets of storage

racks are needed, because of the exchange character of the system; hence, 2*depreracKcost.
The objective function is minimized subject to the following constraints:

$$\sum_{loc \in LOC} X_{ed,loc} = 1 \qquad \forall ed \in ED \qquad [4.2]$$

$$X_{ed,loc} \leq Y_{loc} \qquad \forall ed \in ED, loc \in LOC \qquad [4.3]$$

$$\sum_{ed \in ED} \sum_{loc \in LOC} \left(setuptimerack_{loc} \cdot \#rack_{ed} + degastime \cdot \#tank_{ed} \right) \cdot X_{ed,loc}$$

$$\sum_{loc \in LOC} \left(roadtime_{loc} + setuptime_{loc} \right) \cdot Y_{loc} \leq \#MOBILE \cdot timecp \qquad [4.4]$$

$$X_{ed,loc} \in \{0,1\} \qquad \forall ed \in ED, loc \in LOC \qquad [4.5]$$

$$Y_{loc} \in \{0,1\} \qquad \forall loc \in LOC \qquad [4.6]$$

$$\#MOBILE \in \{0,1,2,...\} \qquad [4.7]$$

Equation [4.2] represents the restriction that all ELV-dismantlers are allocated to exactly one degassing facility. In [4.3] the constraints ensure that an ELV-dismantler can only be allocated to a degassing location that is opened. In equation [4.4], the capacity consumption of the mobile degassing installations is measured in time (timecp). Time is consumed by traveling to the selected degassing locations ($roadtime_{loc}$), setting up at a location ($setuptime_{loc}$), handling of the storage racks ($setuptimerack_{loc}$) and degassing (degastime). The capacity of the mobile degassing installations may not be exceeded, so additional installations are added when necessary. The estimations for the traveling time and the setups are estimates by ARN, and assume that each potential degassing location will only be visited by one degassing installation. In [4.5], [4.6] and [4.7], the domains of the variables are restricted.

4.4.4 Implementation

The models are implemented in AIMMS (Advanced Integrated Multi-dimensional Modeling Software) from Paragon Decision Technology (Bisschop and Roelofs, 2001). AIMMS is an algebraic modeling system with the possibility of easily implementing advanced mathematical models, data connections with databases and graphical user interfaces. Our business version of AIMMS uses CPLEX 7.0 as solver for our programming model. Calculation times for the integer programming model are in the order of a few minutes.

4.5 Results

This section presents the results of our analysis. First, however, some attention is paid to the data and scenarios defined.

4.5.1 Data and scenarios

The ARN databases provide us with all the historical data on the number of wrecks and LPG-tanks dismantled by ELV-dismantlers that are needed for both the vehicle routing and the location-allocation model. The vehicle routing model makes extensive use of a table with distances and driving times based on zip codes. For the optimization model we need data not only on transportation costs, but also on the potential locations for the depots in the regional strategy certified for storage of hazardous waste, and on the degassing facilities (fixed and mobile). Logistics service providers have provided us with a list of 29 potential locations together with an estimation of the rent. Both the engineering company that designed the mobile degassing installation and the company operating the degassing plant provided us with data on the degassing processes required for the location-allocation model. All data are based on the situation of the year 2000.

Transportation costs coming from the vehicle routing model, serving as data input for the location-allocation model, were validated by comparing them with data from logistics service providers for other materials and by examining whether or not they met the expectations of ARN's logistics specialists.

After acquiring and assuring the validity of the data, we fed the data into the models in the base scenarios. In the base scenarios we varied the parameters for the length of the collection period (3 or 4 weeks) and the size of the storage rack (6 or 12 LPG-tanks). We thus had 4 base scenarios, and for each we applied the central and regional strategy, ultimately leading to eight optimizations. From the base scenarios, the most favorable option was selected in cooperation with ARN management. For the selected base scenario we carried out an extensive sensitivity analysis. Sensitivity analysis on the other scenarios did not prove to be essentially different, nor did it provide new insights. To deal with system uncertainty, we carried out sensitivity analysis on the number of LPG-tanks in the most favorable base scenario. The system's redesign is a strategic decision for several years; the number of LPG-tanks has varied over the years, and this is outside ARN's sphere of influence. The yearly quantity of LPG-tanks is thus exogenous. Finally, we performed sensitivity analysis on the cost factors underlying the transportation costs in the most favorable base scenario, because in many cases transportation costs account for almost 50% of the total yearly costs of the system. Besides this, it showed the effects of reductions in the transportation costs on the systems. Figure 4.3 illustrates the base scenarios and the resulting cases for sensitivity analysis.

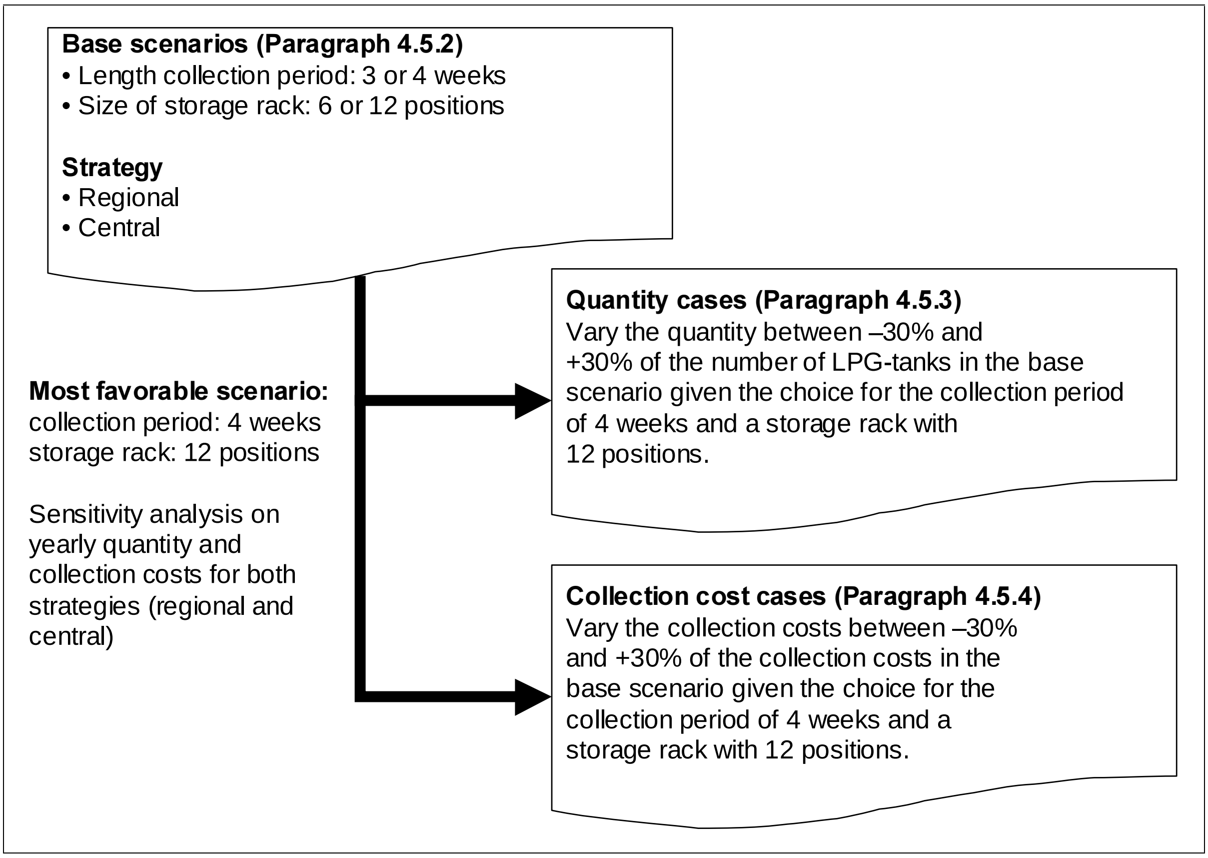

Figure 4.3. Overview of the base scenarios and the resulting cases for sensitivity analysis.

4.5.2 Base scenarios

Table 4.1 provides an overview of the costs for the central and regional strategy for all four base scenarios.

The central strategy is significantly cheaper for all relevant parameter settings than the regional ones. When a collection period of 3 weeks is chosen, the regional strategy is 48% more expensive than the central strategy. When the collection period is 4 weeks, the regional strategy is 8% more expensive. The large difference is caused by the fact that with a collection period of 3 weeks, one mobile degassing installation has too little capacity and a second installation is needed, causing a cost jump of about 200,000 euro. Moreover, when the collection period is 4 weeks only 13 instead of 17 collection rounds will take place per year, which causes another reduction of the total costs.

The effects are small using a storage rack of 6 instead of 12 LPG- tanks. For a collection period of 3 weeks, the storage rack of 6 is about 1% cheaper than that of 12, while for a collection period of 4 weeks, the storage rack of 12 positions is about 1% cheaper than that of 6. This can be explained by the fact that extending the collection period increases more rapidly the number of storage racks needed, when

6-tank racks are used instead of 12-tank racks. For the regional strategy, there is some doubt whether to select two or three depots. The reduction in collection costs, due to the shorter distances when opening an additional depot, may compensate for the increased fixed costs involved. The number of locations to be selected depends on the relative share of the collection costs in the total yearly costs. When the frequency of collection is raised, the relative share of the collection costs increases; hence, three instead of two locations are selected.

Table 4.1. Total costs for the central and the regional strategy in the base scenario.

Central strategy				
Length collection period in weeks	3	3	4	4
Capacity storage rack in LPG-tanks	6	12	6	12
Yearly costs of storage racks	€ 40,000	€ 41,000	€ 45,000	€ 42,000
Yearly transportation / collection costs	€ 219,000	€ 224,000	€ 176,000	€ 172,000
Yearly depot costs	€ 200,000	€ 200,000	€ 200,000	€ 200,000
Total costs	**€ 459,000**	**€ 465,000**	**€ 421,000**	**€ 414,000**

Regional strategy				
Length collection period in weeks	3	3	4	4
Capacity storage rack in LPG-tanks	6	12	6	12
Yearly costs of storage racks	€ 40,000	€ 41,000	€ 45,000	€ 42,000
Yearly transportation / collection costs	€ 167,000	€ 163,000	€ 134,000	€ 136,000
Yearly depot costs	€ 28,000	€ 42,000	€ 28,000	€ 28,000
Yearly costs of mobile degassing facility	€ 399,000	€ 399,000	€ 200,000	€ 200,000
Yearly degassing costs	€ 29,000	€ 29,000	€ 29,000	€ 29,000
Yearly storage costs	€ 16,000	€ 14,000	€ 18,000	€ 14,000
Total costs	**€ 679,000**	**€ 688,000**	**€ 454,000**	**€ 449,000**

4.5.3 Sensitivity analysis in the yearly quantity of LPG-tanks

As mentioned, calculations in the base scenarios are based on quantities of the year 2000, assuming that now all LPG-tanks dismantled by ELV-dismantlers affiliated to ARN are submitted. In the new system, the number of tanks to be degassed is expected to actually come close to this number. However, there always remains some uncertainty with respect to the number of collected LPG-tanks. Sensitivity analysis is therefore performed on the yearly number of LPG-tanks in car wrecks for all scenarios. Table 4.2 displays the results for the scenario in which ARN uses storage racks with 12 positions with a collection period of 4 weeks.

In the sensitivity analysis we are confronted with changes in the number and geographic location of the depots. We therefore analyze both fixing the optimal locations from the base scenario and keeping them open to the model. Increasing the quantity by 10% causes the need for a second mobile degassing installation in the regional strategy; a phenomenon we saw already in the case of a 3-week collection period. In all cases considered, the central strategy seems to be the most attractive solution, keeping in mind that a yearly maximum of about 20,000 LPG-tanks can be degassed with the current facility. If the number of LPG-tanks remains below the numbers in the base case, then the central strategy is definitely the best.

Table 4.2. The influence of variations in the yearly quantity of LPG-tanks on the total costs for a collection period of 4 weeks and a storage rack with 12 LPG-tanks.

Indexed quantity	Total costs of strategy		
	Central	Regional locations free	Regional locations fixed
70	€ 408,583	€ 435,087	€ 435,556
80	€ 408,700	€ 439,227	€ 439,227
90	€ 414,575	€ 443,392	€ 443,415
100	€ 414,869	€ 448,639	€ 448,639
110	€ 418,298	€ 652,924	€ 653,901
120	€ 422,579	€ 660,784	€ 661,216
130	€ 423,891	€ 667,786	€ 670,925

4.5.4 Sensitivity analysis in the collection costs

In many situations the collection costs are close to 50% of the total costs of the system; a right estimation of the collection costs is thus critical. The importance of transportation costs in reverse supply chains is presented in Chapter 3. A great deal of attention has thus been paid to the vehicle routing in this strategic study. In addition, we perform a sensitivity analysis on the collection costs, which may vary, e.g. because of fluctuations in the oil price.

Similar to the sensitivity analysis on the quantity of LPG-tanks, we are confronted with changes in the number and geographic location of the depots. We therefore decided again to analyze both fixing the optimal locations from the base scenario and keeping them open to the model. Table 4.3 demonstrates the changes in costs for the case of storage racks with 12 positions and a collection period of 4 weeks. The central strategy is again the most attractive in all situations, although the difference between the central and regional strategies becomes smaller as the collection costs increase. This can be explained by the fact that one saves on collection costs by adopting the regional strategy with more locations, thereby reducing the total collection costs. However, the differences between the regional strategy with fixed and that with free locations are small, even when the costs are varied by 30%. This indicates the robustness of the optimal solution found by the model. The relative variance is maximally 0.5%, or in absolute terms 3200 euros.

Table 4.3. The influence of variations in the collection costs on the total costs for a collection period of 4 weeks and a storage rack with 12 LPG-tanks.

Indexed collection costs	Total costs of strategy		
	Central	Regional locations free	Regional locations fixed
70	€ 363,145	€ 404,583	€ 407,793
80	€ 380,386	€ 419,740	€ 421,409
90	€ 397,627	€ 434,897	€ 435,024
100	€ 414,869	€ 448,639	€ 448,639
110	€ 432,110	€ 462,255	€ 462,255
120	€ 449,351	€ 475,870	€ 475,870
130	€ 466,592	€ 488,386	€ 489,486

4.6 In conclusion

This chapter discussed a network redesign problem for a case of LPG-tank degassing. Computational complexity, data availability and the problem structure determine the choice of the modeling techniques. We apply an integer programming model to minimize the total costs and to determine the optimal number and the geographic location of the degassing locations. From a modeling perspective, we learned that we require both location-routing models and stochastic location models, but these are computationally complex and data intensive. Data estimation provides the reason for combining location-allocation and vehicle routing models. The ‘error’ that is made when using simple, intuitive models for calculating transportation costs, is not analyzed in this case study. We recommend more research to determine the exact value of the routing in this case. However, with simpler intuitive models, we would not have been able to discern in cost nuances between the different scenarios. Due to the periodic nature of the system, vehicle routing can be applied easily, since routes are fixed. In situations where routes are not fixed but dynamic, and uncertainty cannot be controlled in the way it was in this case, stochastic location-routing models may be a better answer.

The results presented are quite robust, although there can be jumps in the total costs once extra capacity is needed. Given the fact that the expected quantity of LPG tanks is far below the critical ‘jump’ quantity for the central strategy, the central strategy with size 12 racks seems to be the best option. During the results presentation to the management of ARN in February 2002, our quantitative analysis played a crucial role in their choice of the central strategy. A few years ago ARN invested in storage racks with a capacity of 12 LPG-tanks. Since there was no significant cost benefit for a storage rack with a capacity of 6, the use of storage racks with 12 positions is maintained. In the trade-off between costs and the length of the collection period, the management decided for a variant that had not been analyzed: a 4-week period for large ELV-dismantlers and an 8-week period for small ELV-dismantlers. This resulted in lower system costs.

The introduction of this type of periodic system is considered to be successful. The number of tanks submitted for degassing has increased, although a number of LPG-tanks are still leaking out of the system. In 2004, about 79% of the dismantled LPG-tanks were degassed, which is a significant improvement. The representatives and dismantler advisors of ARN continue to stress the importance of proper degassing to dismantlers. In the near future, ELV-dismantlers that still refuse to submit LPG-tanks for degassing will be sanctioned or expelled.

In 2005, the system was further extended with the collection of air-conditioner fluid. ELV-dismantlers were recently trained to dismantle this fluid with specialized equipment. The number of ELVs with an air-conditioner is expected to increase from about 7% in 2005 to about 55% in 2015. The amount of air-conditioning fluid per ELV is very small and stored in small cylinders. Together with the exchange of storage racks of LPG-tanks, the full cylinders with air-conditioning fluid are exchanged for empty ones. Since the capacity occupation of the air-conditioning cylinders is limited, and the transport conditions are comparable to LPG-tanks, the systems for both materials are complementary and thus share the relatively high transportation costs.

Chapter 5

Case study: the value of inventory information for the collection of oils and coolant

“Wanneer men maar zorgt, dat de papieren in orde zijn, staat de overheid een ruime mate van vreedzaam zitten toe.”
Ambtenaar 1e klasse Dorknoper (3444)

The content of this chapter appeared in an adapted form as Le Blanc et al. (2004a). This chapter describes a case study performed in 2003 for Auto Recycling Nederland, dealing with the development of a collection system for oil and coolant. This chapter is focused on the case description and solution. The link between the case conclusion and the theory will be discussed in Chapter 7.

Section 5.1 provides background information on the case study. Section 5.2 elaborates on the newly developed concept called Collector Managed Inventory (CMI), which is the reverse logistics variant of Vendor Managed Inventory (VMI). Section 5.3 explores the related literature. Although some projects described in the existing literature are related to the problem at hand, differences at some crucial points force us to adopt a new approach. Section 5.4 describes the planning methodology and the OR model used to solve the planning problem. Section 5.5 illustrates the value of the information through the application of a CMI strategy in the business case. Section 5.6 briefly presents some results of the analysis of the same system for other materials. Finally, Section 5.7 concludes the case study.

5.1 Problem background

The case study is situated in the network of Auto Recycling Nederland, described in Chapter 2, and deals with oil and coolant. As all other so-called C1 materials, these hazardous materials pose a serious threat to public safety and the environment and must be dismantled within 10 working days after de-registration of the vehicle in the national vehicle register. Other C1 materials include braking fluid, fuel, windscreen washer fluid, batteries and LPG-tanks. Vehicles that are waiting for removal of C1 materials must be stored on an impermeable floor in order to prevent environmental damage. The traditional method for removal of these liquids from ELVs, referred to as drainage, does not meet the latest requirements on safety and the environment, causing accidents and ground pollution. Regarding this as a risky situation, ARN decided to implement, starting in 2003, new drainage systems at the dismantler' sites affiliated to ARN. New equipment safely siphons off liquids from ELVs to a storage reservoir in a closed system. A large storage vessel equipped with remote monitoring is installed for each fluid. Apart from the safety and the environmental aspects, there are collection planning aspects, assisting proactive planning by using data from the remote monitoring equipment, so-called telemetry. This information is valuable and should be exploited, as we will describe in the next section. Summarizing, we analyze the following questions:

- How can the remote monitoring of inventory levels be exploited?
- What are the cost advantages of using remote monitoring?

5.2 Value of inventory information for collection purposes

Over the last decades, advances in information technology have resulted in breakthroughs in supply chain management. A supply chain, referred to as an integrated system that synchronizes series of inter-related processes (Min and Zhou, 2002), benefits from seamless information interchange. Better information results in better planning and coordination within the supply chain. Synchronization or coordination of inter-related processes is enabled by collaboration of supply chain partners. In distribution systems, the coordination of inventory and routing decisions is critical, but the inventory and routing decisions are typically taken separately. The supplier is responsible for delivery of the order (routing decisions), while the customer is responsible for the timing and sizing of inventory replenishment orders (inventory decisions). Bringing inventory and routing decisions under one roof offers the opportunity to quantify the trade-off based on true costs, resulting in a globally optimal solution. Concepts like Vendor Managed Inventory (Disney et al., 2003) and Factory Gate Pricing (Le Blanc et al., 2004b) intend to implement this. We propose the term Collector Managed Inventory (CMI) as the reverse logistics variant of Vendor Managed Inventory. CMI integrates routing and inventory management into one planning process. To the best of our knowledge, these concepts are new in the area of closed-loop supply chains.

5.2.1 The concept of collector managed inventory

In Chapter 3, we indicated that uncertainty is one of the major distinguishing aspects of reverse supply chains. Uncertainty in the behavior of the system is caused by the lack of information and/or control mechanisms regarding quantity, timing, product compositions and quality of supplies. Many reverse supply chains lack good product and inventory data, which causes inefficiencies. In a CMI concept, inventory data reduces uncertainty and hence transportation costs. Collector Managed Inventory is catalyzed by a new information technology called telemetry. Telemetry is the process of gathering information about remote objects and transmitting the information electronically. This facilitates monitoring of inventory levels at a distance and proactive collection planning.

The case study focuses on reverse supply chains of low value recyclables with a negative environmental impact. Storage capacity is limited, and timely collection is often critical, especially when hazardous materials are involved. In the traditional situation, a dismantler contacts the logistics service provider (LSP) to report that a collection should take place within a certain time period, as agreed upon in a service level agreement. The LSP empties the storage vessels and transfers the materials to third-party recyclers. For LSPs, the occurrence of collection orders seems to be random, resulting in reactive ad-hoc collection planning. Telemetry enables the LSP to monitor the storage capacity left at the dismantler's site. Collection can thus be planned several weeks ahead, which is likely to boost efficiency. Due to CMI, the LSP can now estimate when collection should take place and incorporate this in the collection planning. Control of the inventory of recyclables or waste is thus actually transferred from the waste generator, in this case the ELV-dismantler, to the logistics service provider.

5.2.2 Comparing VMI and CMI

Collector Managed Inventory is similar to Vendor Managed Inventory in many ways, although there are two main differences. First, the collection company needs additional incentives to perform on-time collection, assuring availability of storage capacity. In VMI situations, the supplier wants to sell his products and thereby automatically provides inventory availability. Second, the increased efficiency in VMI comes from well-balanced trade-off between inventory and transportation costs. In CMI, the efficiency gains achieved come from foreseeing the moment when collection should take place and actively searching for combination possibilities in planning collection trips, thereby reducing the overall amount of transportation costs. The reason for the focus on transportation costs lies in the low inventory value of returns. Table 5.1 summarizes the similarities and differences between CMI and VMI.

Table 5.1. Comparison of VMI and CMI.

Type of logistics	**Forward logistics**	**Reverse logistics**
Name	Vendor managed inventory	Collector managed inventory
Basic principle	Supplier is responsible for maintaining and replenishing of the inventory of the customer	The collector is responsible for timely collection of recyclables at the dismantler's site
Inventory costs	High inventory holding costs	Low inventory holding costs
Transportation costs	Moderate to low transportation costs compared to value of the product	High transportation costs compared to the value of the product/recyclable
Inventory level	Decreases due to customer demand	Increases due to received returns and dismantling activities
Supply chain motivation	Increased availability, cost reductions	Decreased storage capacity shortage, cost reductions
Applications	Industrial gases, soft drinks, fuel, retail industry	Containers, fluid reservoirs

5.2.3 CMI for the collection of oil and coolant

In this case study we describe the application of the CMI concept in the collection of oil and coolant in the ARN network. The logistics service provider periodically (e.g. weekly) retrieves data on the inventory levels of the storage vessels and constructs a collection plan. The tanker trucks used for collection have two compartments for different fluids. If the data that stems from the telemetry units indicate that one of the materials, oil or coolant, needs to be collected, then both are collected at the same time. Collections can take place for two reasons:

- Volume driven: the storage reservoirs are almost full and collection is needed to prevent capacity shortages.
- Time driven: there is a minimal collection frequency that should be respected.

Minimal collection frequencies are used for materials that diminish in quality over time. Brake fluid is hygroscopic (attract water), for example, and therefore should be collected at least once a year to ensure sufficient quality for recycling.

5.3 Literature

To the best of our knowledge Collector Managed Inventory (CMI) has never been introduced before. While the idea of monitoring the level of refuse or recyclables collected and then dynamically scheduling the collection as an alternative for periodic collection systems is mentioned in Beullens (2001), practical implementation of a CMI system has never been investigated in the closed-loop supply chain literature. The next section examines the most related literature.

5.3.1 Related models in the literature

In the literature on "forward logistics", a number of articles have appeared that describe concepts with similar characteristics as ours. These papers address so-called inventory routing problems. Inventory routing problems involve a set of customers with a certain daily demand that is served from a central depot. The dual objective: to minimize costs and to prevent customers from running out of stock (Dror and Ball, 1987). Applications of inventory routing models that are described in the literature focused mainly on the distribution of industrial gases and soft drinks.

One of the first papers to address the inventory routing problem is Bell et al. (1983), describing a project at a supplier of industrial gases. In this problem, customer inventory levels are forecasted. To avoid shortages in the long-term when solving the short-term operational planning problem, minimum levels are set on the inventory of customers at the end of the planning period. Based on forecast information, the actual scheduling process is solved by a mixed integer linear programming model. The programming model selects from the total set of possibilities the best subset of routes to be driven and the amount to be delivered to each of the customers. The set of possible routes is limited because of the small number of customers on a trip and the many practical restrictions on the routes. All logical routing possibilities are enumerated explicitly and fed into the programming model.

All inventory routing models have to incorporate the long-term effects of decisions taken in the current operational planning period. Dror and Ball (1987) reduce the long-term horizon by considering penalty costs that express the long-term effects of decisions made in the operational planning period. Only full replenishment of inventories is considered. The resulting planning problem is now solved in a three-phase approach. In phase 1, the customers are assigned to days. In phase 2, the vehicle routing problem is solved using a Clarke and Wright savings algorithm (Clarke and Wright, 1964). In phase 3, the solution obtained for phase 2 is improved by local search. Dror and Levy (1986) describe how these improvement methods work for inventory routing.

Dror and Trudeau (1996) investigate the inventory routing problem from a cash flow perspective. Customers are billed immediately with each delivery. Payment for the goods is thus received much sooner, which compensates for the costs of increased frequency of delivery. Dror and Trudeau (1996) do not discuss the operational routing problem. The costs of delivering to a customer are simply estimated by a fixed fee for each delivery.

Herer and Levy (1997) notice the disregard of an appropriate treatment of inventory holding costs in the above literature. They model the problem by incorporating inventory holding costs by so-called *temporal distances*. Customers who are spatially close tend to be on the same route if they are also temporally close, meaning that the optimal delivery periods are not too far apart. The effects of short-term decisions on long-term holding, shortage and fixed ordering costs are incorporated in temporal distances. Temporal distances, defined as the minimal costs of bringing two customers to a common delivery period, are used in the savings calculation of the Clarke and Wright algorithm.

Ong et al. (1996) discuss an application for servicing and re-supplying vending machines in the soft drink industry. These machines need to be visited frequently to collect coins and to re-supply the vending machines. Routing is discussed only for the replenishment crew and not for the service crew, and is based on clustering first, routing second. Clustering is done according to a sweep method. Routing is based on ranking the profits and then applying a first fit algorithm. Improvement of the routing takes place by local tour improvement procedures. The objective is profit maximization. Inventory holding costs and costs of lost sales are ignored in the routing step.

Campbell et al. (2002) describe an application in the distribution of industrial gases. The planning is solved in a rolling horizon in a two-phase approach. In the first step, integer programming is used to determine which customers are visited and how much is delivered. Clustering and aggregation techniques are used to make the integer programming solvable. In the second step, an insertion heuristic combined with several improvement heuristics is used to determine the actual delivery routes. Inventory holding costs are not considered.

5.3.2 Positioning our approach in the literature

The problem settings described in the literature are essentially similar to the reverse logistics setting described in this chapter. Instead of delivering gases or soft drinks, one delivers storage space for oils and fuels. Nevertheless, the ARN setting features some unusual characteristics that justify a new model. First, due to the low or sometimes even negative value of the cores or materials to recycle, the inventory holding costs are irrelevant. Collecting as much as possible in one visit is the thing to do, thereby minimizing transportation costs. Models described in the literature where the inventory costs are neglected typically concern situations with high demand, so that intervals between two consecutive visits are short. In the case at hand, inventory

costs also do not matter, but the supply rate of the liquids is low; i.e. the time period between two consecutive visits is long. Second, the demand for the beverages and gases described in the literature is unknown and sometimes difficult to estimate; consider, for example, the demand for heating oil, which depends on the weather. In our problem setting, we have the opportunity to obtain accurate information on the inventory levels of fluids at the ELV-dismantlers, due to the online monitoring of the filling of the reservoirs.
The next section describes our method of solving the collector managed inventory problem.

5.4 Methodology

Although telemetry allows for online monitoring, we assume a periodic review of inventory levels for two levels. First, the planning of the vehicles for collection is not a continuous process, but is performed once or twice a week. Second, the information is obtained by using a dial-up network. After retrieval of the data with the telemetry units, a collection plan is constructed for the coming review period. A review period equals the planning period. An order, triggered either by volume or by time, must be performed in the next review period. We call these orders “must-orders”.
We also consider the possibility of visiting dismantlers that do not directly need a collection but are close to triggering one and can be inserted in the route at low marginal costs. These orders are called “can-orders”. Can-orders are used to profitably fill up the remaining capacity of collection trucks, but can never initialize a new collection trip. An additional difference is that can-orders can be performed partially, meaning not fully emptying the storage reservoir, but only as far as capacity left in the truck allows; with must-orders, however, the logistics service provider is obliged to fully empty the storage reservoir.

Figure 5.1 provides a conceptual overview of the must-order level, can-order level, must-order time and can-order time for a given storage reservoir at a dismantler site. Inventory levels are monitored at the beginning of each period, in the base scenario weekly. When a dismantler passes one of the must-order lines, a must-order is generated that will be part of a route; if a can-order line is passed, but not a must-order line, a can-order is generated for possible insertion in a must-order-driven route. If one of the materials in a material group triggers an order, the order is generated for the whole material group.

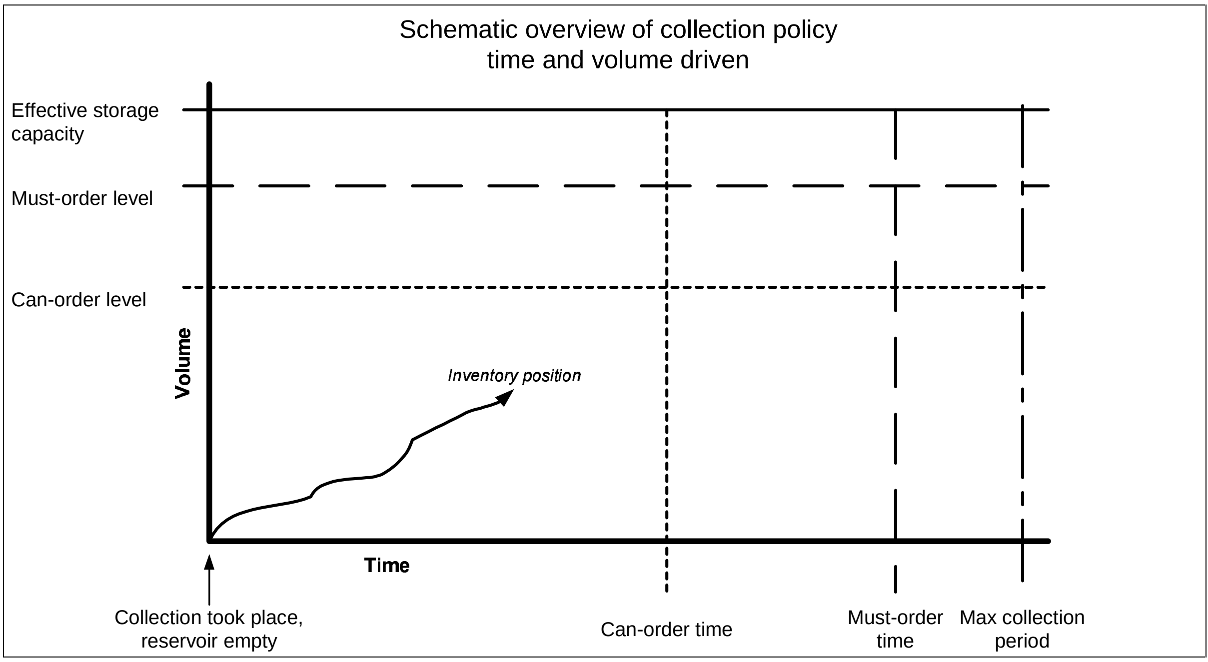

Figure 5.1. Conceptual overview of triggering orders in collection planning.

The must-order level is defined analogously to the reorder-point in inventory management (see e.g. Silver et al. (1998)). We assume that the material supply per day for material mat of dismantler ed is normally distributed with mean $\mu_{ed,mat}$ and variance $\sigma^2_{ed,mat}$. The storage capacity for material mat of dismantler ed is given by $cap_{ed,mat}$. The length of the review period is denoted by rp. The collection takes place within the review period, so the response time is at most rp days; we assume that the response time is uniformly distributed.
The must-order level, $mo\_level_{ed,mat}$ for dismantler ed and material mat is given by equation [5.1].

$$mo\_level_{ed,mat} = cap_{ed,mat} - 1\tfrac{1}{2} \cdot rp \cdot \mu_{ed,mat} - k_{ed,mat} \cdot \sqrt{rp \cdot \left(1\tfrac{1}{2} \cdot \sigma^2 + \tfrac{1}{12} \cdot \mu^2 \cdot rp\right)} \qquad [5.1]$$

Here, $k_{ed,mat}$ denotes a safety factor that is used to capture the uncertainty within the review period. The safety factor can easily be calculated using the standard normal distribution and the desired service level. The can-order levels $co\text{-}level_{ed,mat}$ are calculated according to equation [5.2].

$$co\_level_{ed,mat} = mo\_level_{ed,mat} - \alpha_{ed,mat} \cdot rp \cdot \mu_{ed,mat} \qquad [5.2]$$

Here, $\alpha_{ed,mat} \in \{0,1,2,\ldots\}$ expresses the number of review periods that we plan ahead for can-orders driven by volume. The must-order time, $mo\_time_{ed,mat}$, is based on the maximum allowed number of days between two collections, max collection time, resulting in equation [5.3].

$$mo\_time_{ed,mat} = \text{max collection time} - rp \qquad [5.3]$$

The can-order time is calculated using $\beta_{ed,mat} \in \{0,1,2,\ldots\}$, expressing the number of review periods we look ahead for can-orders driven by time. This results in equation [5.4].

$$co\_time_{ed,mat} = mo\_time_{ed,mat} - \beta_{ed,mat} \cdot rp \qquad [5.4]$$

If the parameters $\alpha_{ed,mat}$ and $\beta_{ed,mat}$ equal zero for all dismantlers and materials, this corresponds to a policy without can-orders.

The inventory positions of all storage reservoirs for all dismantlers are retrieved at the beginning of each review period. This allows the must-orders and can-orders to be generated, and a collection plan for the coming period to be made. This plan is constructed by the generation of feasible routes and the subsequent selection of the optimal combination of routes from this set by solving a set partitioning problem.
The remainder of this section explains our algorithm for the generation of routes and gives insights into constructing and solving the resulting set partitioning problem.

5.4.1 Route generation

In the route generation, all possible routes are generated. Feasible routes are added to the set partitioning tableau. A route is feasible if the maximum time allowed for one day and the maximum capacity of one of the reservoirs in the truck are not exceeded. Strictly speaking, the amount to be collected changes slightly during the review period, due to ongoing dismantling activities. This is neglected: we assume the amount of fluids in the order fixed in the route generation.
Since the number of orders considered per period is relatively small, and the number of orders that fit in a route is limited, explicit enumeration of all possible routes is possible. The difficulty in route generation is to enumerate all combinations in a systematic and efficient way. Our route generator consists of two main procedures that are recursively used: *MustOrderInsertor* and *CanOrderInsertor*. These procedures aim to add an unplanned must- and can-order, respectively, to the route. The route generation process starts with an empty route and a call to the procedure *MustOrderInsertor*. We use a best insertion algorithm for inserting both must- and can-orders in the route. Setup, loading and unloading times, based on the amount of fluids, for both the must- and can-orders, are incorporated in the route generation. If a route is found feasible, it is written to the set partitioning tableau, and the next iteration is started to try to add more orders. If a route is found to be unfeasible, the order last added is removed from the route and a new attempt is made to add the next order in the list. Figure 5.2 provides an overview of these two main procedures.
Note that we allow for the partial insertion of can-orders. This occurs when there is not enough capacity left to collect the full amount of the can-order. Section 5.5 will examine both full and partial collection of can-orders. Must-orders are always collected completely.

```
Function MustOrderInsertor

FOR ( MOrder in UnplannedMustOrderList ) DO
        RouteFeasible = MustOrderBestInsertionInRoute( MOrder )
        Remove MOrder from UnplannedMustOrderList
        IF( RouteFeasible ) THEN
                WriteRouteToSP
                MustOrderInsertor
                CanOrderInsertor
        ENDIF
        MustOrderRemoveFromRoute( MOrder )
        Add MOrder to UnplannedMustOrderList
ENDFOR

Function CanOrderInsertor

FOR ( COrder in UnplannedCanOrderList ) DO
        RouteFeasible = CanOrderBestInsertionInRoute( COrder )
        Remove COrder from UnplannedCanOrderList
        IF( RouteFeasible ) THEN
                WriteRouteToSP
                CanOrderInsertor
                ENDIF
        CanOrderRemoveFromRoute( COrder)
        Add COrder to UnplannedCanOrderList
ENDFOR
```

Figure 5.2. Outline of the route generation algorithm.

During the route generating process, the costs of the route are calculated and corrected for the costs of insertion of can-orders, the future savings. These cost savings, as shown in [5.5], are based on the difference between the costs of insertion in the current route and the costs of a separate route for this order (linehaul), corrected for the amount of material. This savings mechanism evaluates the benefit of adding a can-order to the existing route compared to waiting until collection is necessary, i.e. a must-order is generated. It acts as the selection mechanism for can-orders.

$$\begin{aligned} \text{cost\_savings}_{ed} &= \text{insertion\_cost}_{ed} \\ &- \frac{\text{linehaul\_cost}_{ed}}{\sum_{mat} \text{linehaul\_volume}_{ed,mat}} \cdot \left(\sum_{mat} \text{inserted\_volume}_{ed,mat} \right) \end{aligned} \qquad [5.5]$$

<u>Example</u>

Consider an ELV-dismantler having a maximum storage capacity for 3,000 liters of oil and 2,000 liters of coolant. The costs of collecting these materials in a linehaul, when both vessels would be full equal € 200 (i.e. € 0.04 per liter). At a given moment, this ELV-dismantler can be inserted in a route as a can-order at insertion costs of € 90. The total quantity that can be collected of both oil and coolant is 4,000 liters. The estimated cost savings of inserting this can-order using formula [5.5] amount to € 70.

The same cost savings are used for must-orders in non-empty routes, because combining must-orders to the greatest extent possible in a given route reduces the total number of routes to be driven. This is necessary for must-orders, since driving two routes with one must-order in each route, combined with a number of can-orders, would otherwise be evaluated as better than driving one route with both must-orders.

5.4.2 Route selection

We formulate the problem of finding a collection of routes such that all must-orders are fulfilled at minimal costs as a linear integer programming problem. In this problem we define vehicle-day combinations as the maximum number of routes that can be selected, due to the number of days and vehicles available. After the introduction of some notation, this problem is given in equations [5.6] to [5.12] below.

Variables

$X_{r,vd}$ = 1 if route r is chosen for vehicle-day combination vd, 0 otherwise.
sc_{co} = 1 if can-order co is not fulfilled in the chosen routes, 0 otherwise.
sv_{vd} = 1 if vehicle-day combination vd is not used to fulfill the chosen routes, 0 otherwise.

Parameters

c_r = the costs of route r, corrected for can-orders and multiple must-orders in the route.
$a_{mo,r}$ = 1 if must-order mo in route r, 0 otherwise.
$a_{co,r}$ = 1 if can-order co in route r, 0 otherwise.

The route selection problem

$$\min \quad \sum_{r}\sum_{vd} c_r \cdot X_{r,vd} \qquad [5.6]$$

$$\text{s.t.} \quad \sum_{r}\sum_{vd} a_{mo,r} \cdot X_{r,vd} = 1 \qquad \forall mo \qquad [5.7]$$

$$\sum_{r}\sum_{vd} a_{co,r} \cdot X_{r,vd} + sc_{co} = 1 \qquad \forall co \qquad [5.8]$$

$$\sum_{r} X_{r,vd} + sv_{vd} = 1 \qquad \forall vd \qquad [5.9]$$

$$X_{r,vd} \in \{0,1\} \qquad \forall r, vd \qquad [5.10]$$

$$sc_{co} \in \{0,1\} \qquad \forall co \qquad [5.11]$$

$$sv_{vd} \in \{0,1\} \qquad \forall vd \qquad [5.12]$$

Equation [5.6] describes the objective function of the optimization problem, which is total cost minimization of the collection plan. Equation [5.7] represents the constraints ensuring that each must-order is inserted exactly once. Equation [5.8] represents the constraints ensuring that each can-order is inserted once, at most. Equation [5.9] ensures that each vehicle-day combination has at most one route. Equations [5.10] to [5.12] bound the domain of the variables. The variables sc_{co} and sv_{vd} in constraints in [5.8] and [5.9] serve as slack variables to make the problem a pure set partitioning problem; the constraints in [5.8] and [5.9] would otherwise be smaller than or equal to equations.

Compared to generic integer programming, set partitioning has the benefit that the problem structure can be exploited to solve the problem more efficiently (Balas and Padberg, 1976). To solve the set partitioning instances, we use a solver developed by Van Krieken et al. (2004). The main building blocks of the solver are provided by Lagrangean relaxation for determining the lower bounds and branch and bound for finding the optimal solution (Fleuren, 1988). Furthermore, several problem reduction techniques are used to reduce the number of variables and constraints in the problem, for details see Van Krieken et al. (2003). The solver is highly efficient in solving the set partitioning instances under consideration, even if the amount of variables grows very large. Problems with over 5 million variables are solved in a couple of minutes on a normal desktop computer. Generic linear programming based solvers are less able to exploit the special structure of set partitioning problems, and take more time, on average, to solve these instances.
In many instances, the number of vehicle days available exceeds the number of must-orders. In these cases the vehicle-day combination becomes irrelevant, because there will never be more routes than must-orders. When this is the case, the number of variables can be reduced proportionally to the number of vehicle-day combinations.
In some cases, the generated set partitioning problem is unfeasible, because the available capacity (vehicle-day combinations) is too small to fulfill all the must-orders. To overcome this, we have added a dummy route for each must-order. This dummy route covers only one must-order, and the costs of this route are equal to a high factor times the costs of a linehaul. These costs represent the costs of an emergency order and ensure that the dummy route will be chosen only if it is not possible to fulfill the order on a vehicle-day combination.

5.5 Results

5.5.1 Data and scenarios

We simulate a horizon of ten years, divided into runs of one year. In the base scenario we use a review period of one week; in total, we simulate 522 collection or review periods. Collection should take place at least once a year; i.e. all ELV-dismantlers are visited at least ten times in the simulation. The initial inventory at the

first review for each of the 267 ELV-dismantlers is generated randomly. We always use the same initial situation in order to make a fair comparison with each scenario.
A tanker truck with a capacity of 7600 liters for oil and 5700 liters for coolant is rented for the collection. The logistics service provider rents these tanker trucks including the driver; ARN is therefore charged only for the amount of usage, expressed in the number of hours and kilometers driven: 60 euro per hour, 0.38 euro per kilometer driven. A regular workday consists of 450 minutes; after that, the charge per hour is doubled for the next 240 minutes. The starting and unloading point is the current depot for oil and coolant, located in Lelystad, the Netherlands.

5.5.2 Base scenarios

The situation with reactive planning coincides with the situation in which can-order level $\alpha_{ed,mat}$ and can-order time $\beta_{ed,mat}$ are both equal to 0; see equation [5.2] and [5.4]. A proactive approach implies a can-order level $\alpha_{ed,mat}$ and a can-order time $\beta_{ed,mat}$ larger than 0. We consider only those policies where the degree of looking ahead is the same for both volume-driven and time-driven collection; i.e. α and β are equal. We varied $\alpha_{ed,mat}$ and $\beta_{ed,mat}$ between 0 and 6, where we made no differentiation between either ELV-dismantlers or materials. The results for different can-levels and can-times are shown in Table 5.2.
We observe that a possible cost reduction up to 18.9% is realized by adopting a forward-looking strategy. The number of routes necessary for collection, which is equal to the number of vehicle days, as well as the average distance traveled within each route, is reduced. The total number of kilometers driven per year is reduced by about 18,700. Consequently, it is hardly surprising that the load-factor, defined as the maximum fraction of capacity of the truck used in a route, is increased from 0.67 to 0.93. The marginal benefit in costs diminishes as the number of review periods looking ahead increases. Extending the forward-looking horizon further than 6 weeks seems to make no sense. Furthermore, for some very large ELV-dismantlers it corresponds to always triggering a can-order.

Table 5.2. Results for oil and coolant with fractional collection of can-orders.

α (can-order level) = β (can-order time)	0	1	2	3	4	5	6
Average # must-orders per week	7.17	5.50	4.98	4.66	4.53	4.45	4.43
Average # can-orders per week	0.00	2.13	2.80	3.28	3.47	3.61	3.67
Average # routes per week	3.95	3.41	3.34	3.27	3.26	3.23	3.23
Average route distance (km)	345.1	337.7	326.2	320.6	315.0	313.0	310.9
Average route duration (min)	541	562	556	556	551	552	550
Average load-factor	0.671	0.840	0.883	0.909	0.923	0.927	0.931
Kilometers driven per year	71,091	60,178	56,824	54,758	53,613	52,709	52,387
Costs per year (normalized)	100.0	89.5	85.7	83.7	82.3	81.6	81.1

Table 5.3. Results for oil and coolant with full collection of can-orders.

α (can-order level) = β (can-order time)	0	1	2	3	4	5	6
Average # must-orders per week	7.17	6.20	5.64	5.38	5.22	5.08	4.98
Average # can-orders per week	0.00	1.00	1.63	1.98	2.26	2.47	2.65
Average # routes per week	3.95	3.69	3.58	3.54	3.45	3.42	3.39
Average route distance (km)	345.1	348.7	348.1	342.2	344.6	341.6	337.0
Average route duration (min)	541	558	563	560	568	568	566
Average load-factor	0.671	0.707	0.733	0.754	0.773	0.781	0.800
Kilometers driven per year	71,091	67,090	65,025	63,239	62,062	60,976	59,582
Costs per year (normalized)	100.0	96.7	94.9	92.8	92.1	91.0	89.5

In the base scenario described above, we assume that partial execution of can-orders is allowed. Table 5.3 gives the results of a scenario, in which we restrict the model to allow only full collection of can-orders. In this scenario, a still significant cost reduction of 10.5% is possible when we adopt the same proactive strategy. The load-factor is increased up to 0.80, which is significantly less than in the situation where we allow for fractional can-orders. Figure 5.3 and Figure 5.4 illustrate the collection costs and the load-factor for both scenarios; the vertical lines in Figure 5.3 indicate the 90% confidence intervals. The figures illustrate the decrease of the marginal cost savings by extending the look-ahead horizon. The marginal savings decrease, since once the number of can-orders is large enough, additional planning combinations do not add significant benefits. Practically, a forward-looking period of 3 weeks ($\alpha_{ed,mat}$ = $\beta_{ed,mat}$ = 3) seems to be enough to fully exploit the saving potential.

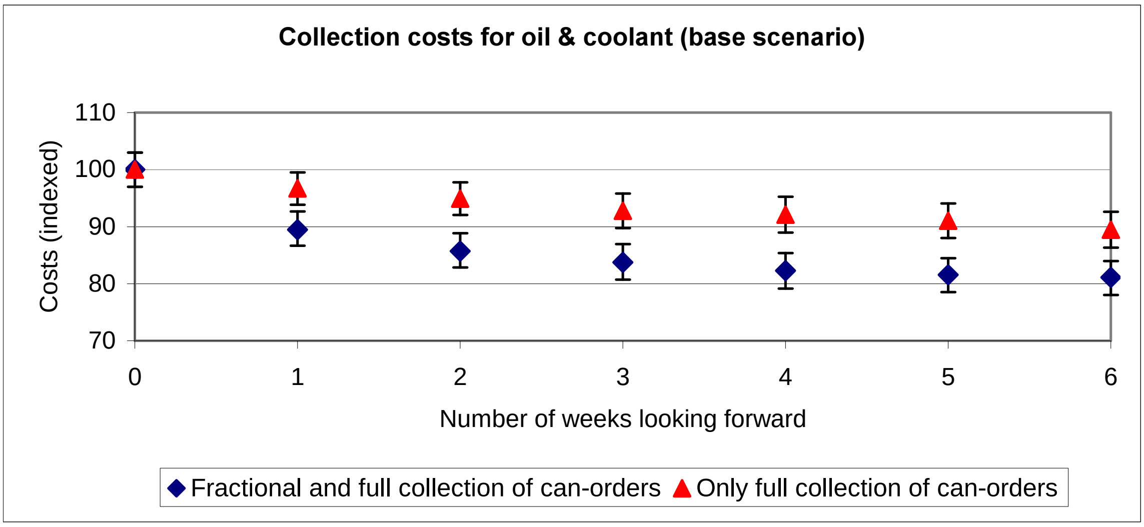

Figure 5.3. Overview of the yearly collection costs in case of fractional and full collection of can-orders.

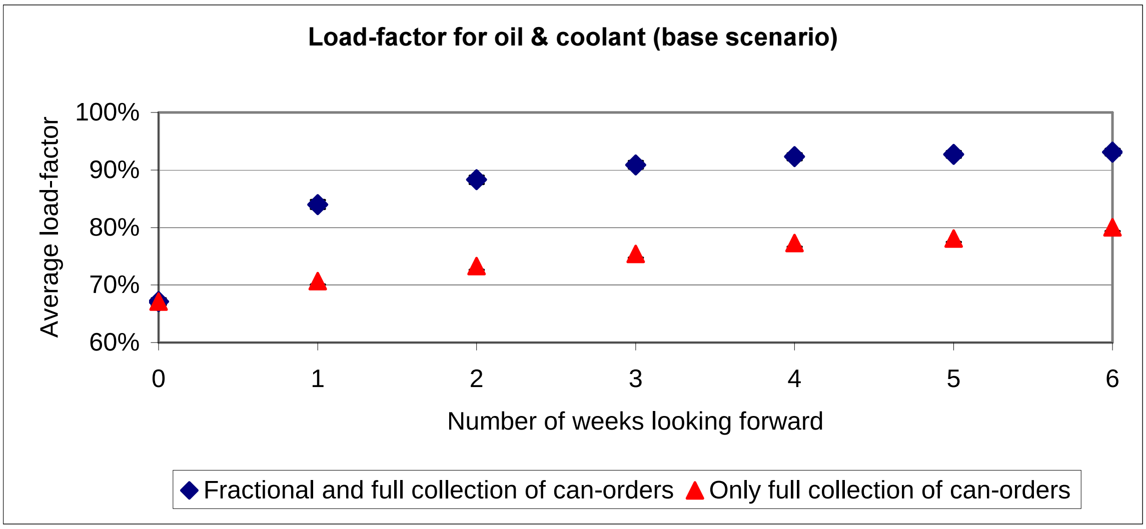

Figure 5.4. Overview of the average load-factor in case of fractional and full collection of can-orders.

5.5.3 Sensitivity analysis on the length of the review period

The choice for the weekly data review of the telemetry units and construction of the collection planning is a somewhat arbitrary management decision. If this frequency is increased, we expect that the performance will increase as well, since we can plan the trips more frequently, using more actual data. However, when the length of the review period is longer, more possibilities exist to combine orders and create more efficient routes. Figure 5.5 and Figure 5.6 depict the costs and the load factor for different lengths of the review period. In a reactive strategy, longer review periods perform better, which is a result of having more combination possibilities. This offsets the cost effect that a longer review period results in a lower must-order level, which effectuates more must-orders and hence earlier collection. This might not be the case once the review period becomes extremely long, and the total costs may rise. Long review periods, however, contradict the methodology of using telemetry. Adopting a proactive, forward-looking strategy provided us with better combination possibilities compared to the non-forward-looking, reactive strategy. In short: the more proactive the strategy, the higher the planning frequency should be. The relative improvement of changing the planning frequency is small, however, compared to the shift from reactive to proactive planning. Since review periods of one week are more convenient, ARN chooses a proactive strategy with a one-week review period.

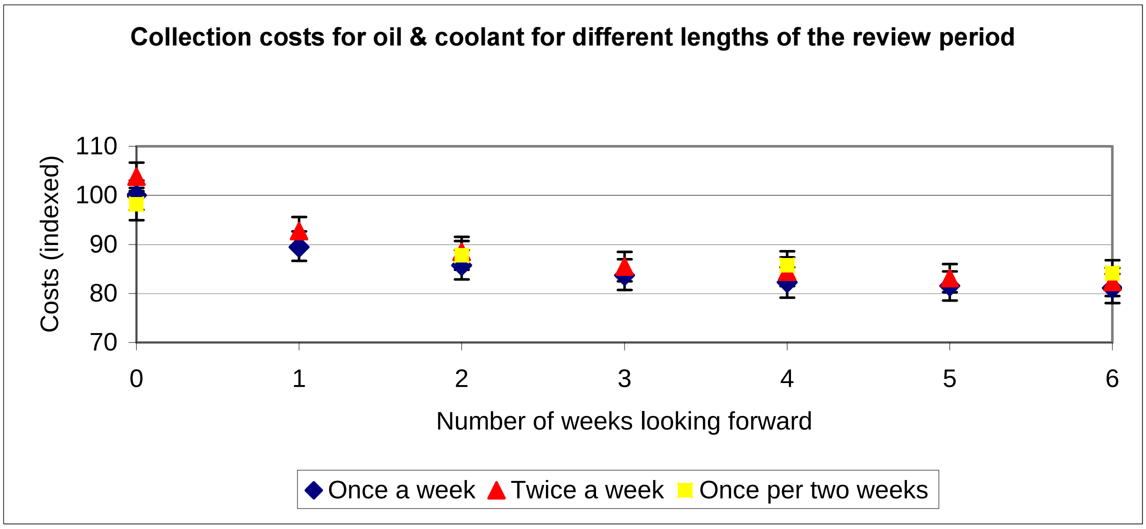

Figure 5.5. Overview yearly collection costs for different lengths of the review period.

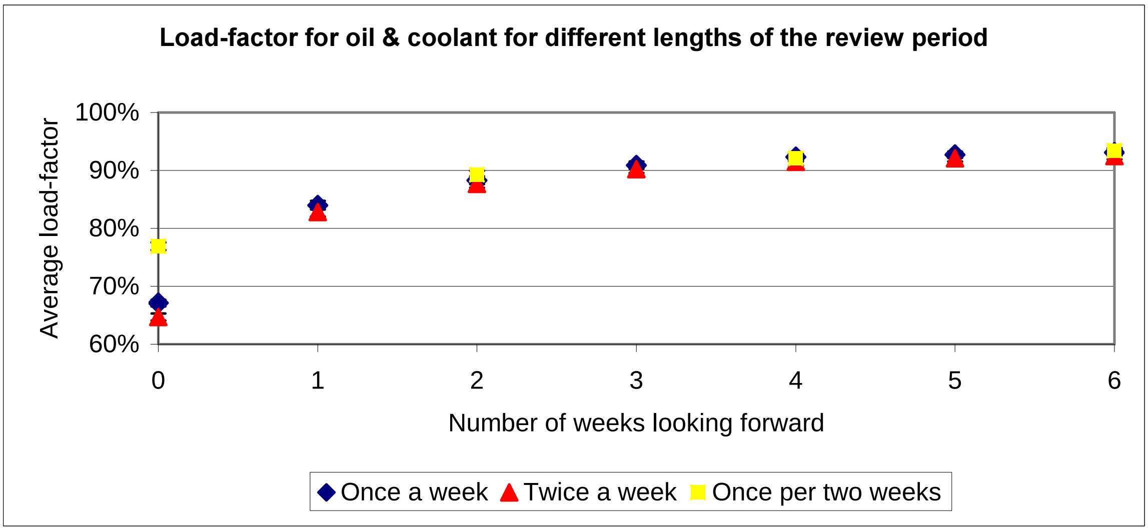

Figure 5.6. Overview of the average load-factor for different lengths of the review period.

5.6 Other applications

Motivated by the promising results for oil and coolant, ARN management initiated research on the application of the same methodology for the collection of other materials. This section briefly discusses the results of the attainability studies on:

- The proactive collection of fuels and windscreen washer fluid
- The proactive collection of containers

5.6.1 The collection of fuel and windscreen washer fluid

Extending the system for other fluids drained from ELVs is a logical next step. The vessels for fuel and windscreen washer fluid at the ELV-dismantler sites are equipped with the same technology. The model presented in this chapter is used to investigate the potential benefit for fuel and windscreen washer fluid. Adaptations were limited and concerned only changes of the data. Especially the amount of liquids is less; an ELV contains only about 1 liter of windscreen washer fluid and 1 liter of fuel; most is reused directly.

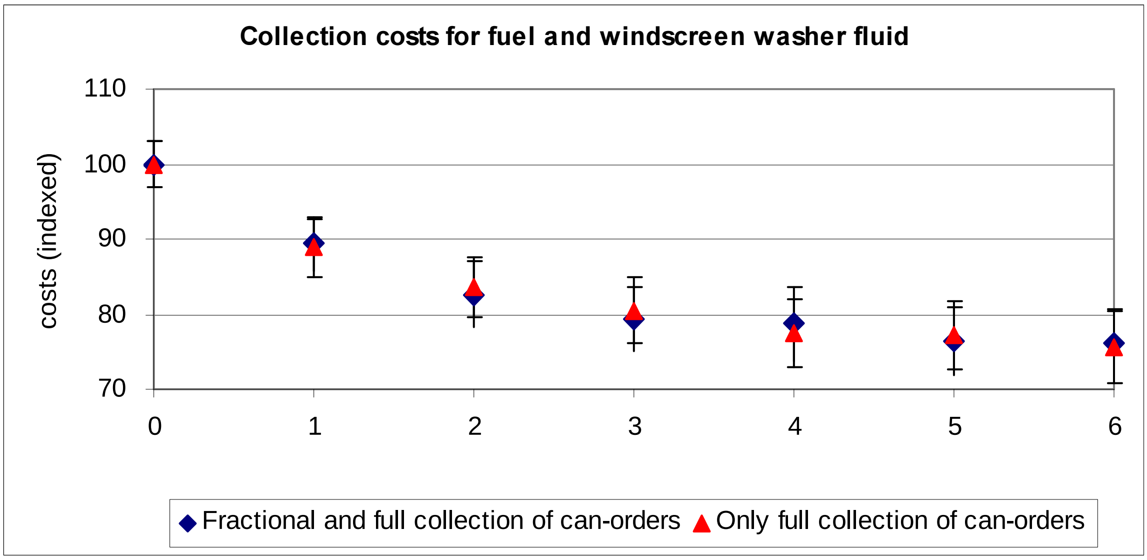

Figure 5.7. Yearly collection costs in case of fractional and full collection of can-orders for fuel and windscreen washer fluid.

Figure 5.7 shows the analysis results for the collection of fuel and windscreen washer fluid. The potential relative cost savings are higher than for the scenarios with oil and coolant. The limited amount of liquids to be collected, which makes the network less dense, favors proactive policies. Since the maximum route duration limits the trip length instead of the vehicle capacities, the benefit of allowing partial collection of can-orders, instead of only full collection, is insignificant.

5.6.2 The collection of bulk materials

High volume materials dismantled from ELVs such as PU foam, rubber, glass, tires and bumpers are stored and collected in containers. The logistics costs for these materials are among the highest in the reverse network of ARN. Small relative improvements would imply large absolute cost savings. A full description of this research is described in Schreurs (2004) and published in Le Blanc et al. (2005).

Obtaining inventory information, i.e. the filling of containers using telemetry, is difficult and expensive. We therefore consider, as an alternative, the use of a forecasting model on the filling of ELV-dismantler containers. This model is based on the following:

- The ratio between the amount of time passed since the last collection and average time between two collections.

- The ratio between the number of current number deregistrations and the average number of deregistrations between two collection requests.

In the analysis we compared three different levels of inventory information:

- Degree 1: there is no information on inventory levels. A container is collected only if the ELV-dismantler indicates that the container is full. This scenario corresponds to the current situation.
- Degree 2: inventory levels are forecasted, and the forecasts, together with the collection requests of the ELV-dismantlers, are used to construct the collection planning.
- Degree 3: inventory levels are known accurately at any time: "perfect information". The logistic service provider can plan the collection of containers proactively. To obtain this level of information, expensive sensors are needed to determine the levels of the containers at the ELV-dismantlers.

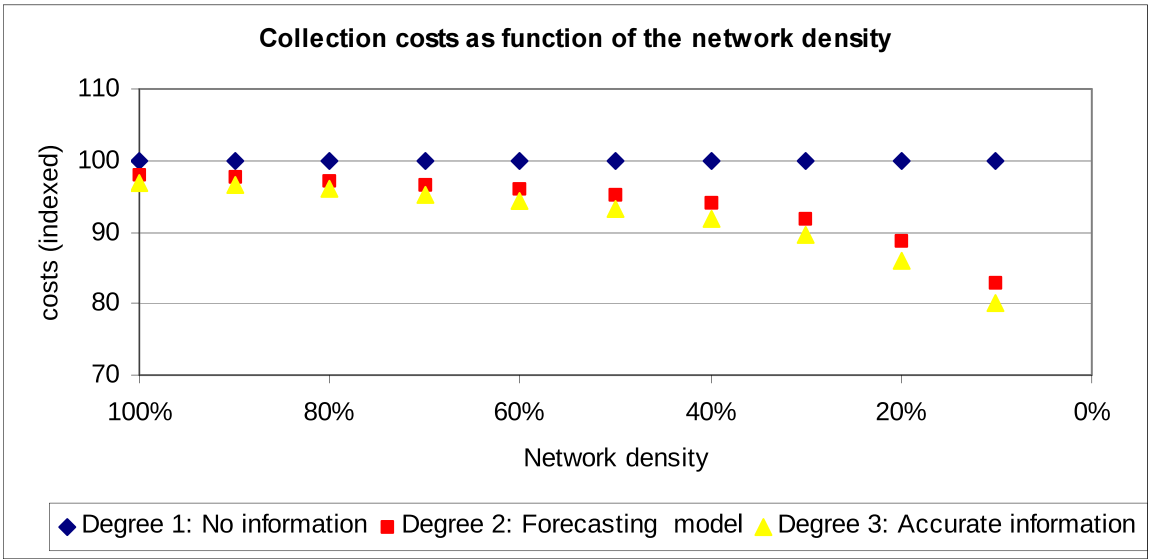

Figure 5.8. Collection costs of each information level for different network densities (the costs of degree 1 always equal 100).

Results show that the effect of proactive planning is limited. Using the forecasting model, total costs can be reduced by 2%. If we have accurate information about the inventory levels, we can save 3.1% on the total costs. The limited cost savings can never offset the implementation costs. Intrigued by this result, we investigated further the influence of network density. This was done by assuming that a lower volume of materials is collected; e.g. a network density of 60% implies that the amount of materials collected from each vehicle drops by 40%. Figure 5.8 shows that the lower the network density, the higher the relative value of information by proactive planning, due to fewer combination possibilities.

The case study in Chapter 6 further investigates planning concepts for the collection of containers.

5.7 In conclusion

The application of remote monitoring of inventory levels in reverse logistics enables the concept of Collector Managed Inventory (CMI). A newly developed planning methodology supports the logistics service provider in constructing operational planning schedules by using the information coming from the telemetry units placed at the ELV-dismantlers. It is now possible to foresee when collection should take place and actively search for combination possibilities in planning collection trips, thereby reducing transportation costs. Two types of transportation orders are considered: must- and can-orders. Must-orders have to be collected in the current period, while can-orders are collected only if they can be combined efficiently with the must-orders. This offers the opportunity of planning orders proactively and saving on transportation costs. The potential is illustrated in a real-life case for the collection of oil and coolant at Auto Recycling Nederland. Cost savings amount to 18.9% when we compare proactive collection planning with traditional reactive collection planning. The system is operational as of 2005, together with a similar system for the collection of fuel and windscreen washer fluid, which we briefly discussed in Section 5.8.
We also investigated the potential of the system for containers. The network density proves to be the critical determinant, and the benefits in this case were small. Research on a wider application of the CMI concept for other types of returns in closed-loop supply chains is of interest. Telemetry helps in reducing the uncertainty that characterizes and complicates closed-loop supply chain management. The telemetry units that measure the amount of liquids in a reservoir are well-developed and have become cheaper during the last decade. This makes application in the reverse logistics setting attractive. In forward supply chains accurate data on inventory levels is obtained from the information system; in reverse supply chains, these information systems are usually absent. Similar applications of the use of telemetry units in reverse logistics are not yet well-developed, despite of the great opportunities of applying these concepts in other settings. Consider, for example, press containers that are used to collect garbage. Depending on the resistance of the press, the load of the container can be determined and sent to the logistics service provider by the telemetry unit. This should be within reach soon, considering the decreasing costs of information and telecommunication technology, as it is today utilized in forward supply chains.

Chapter 6

Case study: planning concepts in the closed-loop container network

“Terwijl de wereld schreeuwt om grotere slijtage, worden er nog steeds huizen gebouwd die langer dan tien jaren meegaan. Onverantwoordelijk!”
Amos W. Steinhacker (6944)

The case study described in this chapter appeared as Le Blanc et al. (2004c). The study, performed in 2004, aimed at quantifying the expected benefits of new planning concepts for the logistics network for containers of Auto Recycling Nederland. In this chapter, we restrict ourselves to the case study; reflection on the propositions of Chapter 3 will be done in Chapter 7.
The problem and its real-life setting are discussed in Section 6.2. Section 6.3 discusses the literature relating to the problem at hand. Vehicle routing literature describing similar problems is scarce. On account of the particular characteristics of the problem, we develop a new heuristic, which is described in Section 6.4. The scenarios and the setup of the research are covered in Section 6.5. Section 6.6 discusses the results, the sensitivity analysis and the results of alternative scenarios. Finally, Section 6.7 summarizes the results and suggests directions for further research.

6.1 Problem background

The case study deals with optimizing the collection of containers in the ARN network, as described in Chapter 2. Containers are used in the ARN system to store and collect manually dismantled, high-volume materials. These materials - glass, PU foam, rubber strips, tires and bumpers - contribute significantly, representing about 8% of the average vehicle weight, to ARN's current recycling quota. The logistics costs of these materials are high. Due to pressures from the market, ARN needs to improve further the efficiency of the reverse chain. This case study analyzes a routing concept to reduce costs.

6.1.1 Routing concepts

Being the chain director, ARN outsources the actual processes to existing ELV-dismantlers, shredder companies, recyclers and logistics service providers (LSPs) as described in Chapter 2. The LSPs, contracted for a period of three years, are responsible for the execution of logistics activities in a certain district, referred to as province. Their activities include the transportation of the containers to a depot, consolidation at the depot, in some cases value-adding activities such as sorting and, finally, transportation to the recycling company. The planning is currently decentralized and carried out by the individually contracted LSPs, which are assigned to ELV-dismantlers on the basis of provincial boundaries.

ARN could use its position to centralize the planning. In a centralized planning scenario, transportation orders would not be sent directly to the individual LSPs, but would be collected on a centralized level and assigned in clusters to the LSPs, thereby making use of the cost benefits of combining orders. Hence, allocation of ELV-dismantlers to LSPs would no longer be fixed, but adjusted regularly based on the optimization of routes on a central level. Cruijssen and Salomon (2004) call this the principle of transportation order sharing. They find savings up to 15% in an empirical study, depending on the characteristics of the network. In the literature, this concept is referred to as fourth-party logistics (4PL), where the fourth-party represents an entity above the supply chain organizations that assembles and integrates third-party capabilities to achieve transformational efficiencies for the supply chain (Bumstead and Cannons 2002).

The operational process of ARN is organized as follows. An ELV-dismantler with a full container submits a request for collection to the logistics service provider (LSP). Within five working days, the LSP visits the dismantler and exchanges the full container for an empty one. Glass, rubber strips and PU foam are collected in a compartmented container, specially designed for ARN. Tires and bumpers are collected in 35m3 containers for all ELV-dismantlers. Currently, all materials are brought to the depot, where they are all, except tires, sorted and processed and then transferred by bulk transport to recyclers, mostly located in neighboring countries. Since tires need no processing at the depot and the four contracted recycling companies are located in the Netherlands, they can be sent directly to recyclers, bypassing the depot. This study examines the cost benefits of this option. Since the

recyclers of materials other than tires are located abroad, transport of these materials to the recyclers usually takes place by a linehaul trip. Linehaul trips offer no combination possibilities, and the costs of these trips are assumed to be fixed.
Next to the provincial boundaries, there is another major constraint. Currently, LSPs use two types of lifting mechanisms for loading and unloading containers onto a truck. The first system uses an iron chain to drag the container up onto the truck, while the second system uses a pneumatic hook to pick-up the container and place it on the truck. Although both systems work adequately, they are not compatible. A container or truck suitable for the hook system is not suitable for the chain system, and vice versa. This restriction must be taken into account in planning the trips, since LSPs do not have both lifting mechanisms, which leads to a complexity-reducing separable structure. We expect that standardization of the lifting mechanism would be an improvement. Figure 6.1 shows the map of the Netherlands with provincial boundaries and the lifting mechanism in use (hook or chain).

Figure 6.1. Overview of the ARN network indicating the two lifting mechanisms (hook and chain) in use per province.

6.1.2 Goal of the study

The study aims to analyze and improve the system of collecting containers. To this end, we explore the following questions:

- What are the effects on the logistics performance of allowing direct shipment of containers with tires from dismantler to recycler, bypassing the consolidation depot?
- What are the effects on the logistics performance of changing the allocation of dismantlers to LSPs from the current assignment (based on provincial boundaries) to optimally fixed assignment or to dynamic assignment (based on optimal routing decisions in each planning period)?
- What are the effects on the logistics performance of standardizing the lifting mechanism for loading and unloading containers onto a truck?

Although this is mainly a tactical study, we again choose to solve the operational problem as well, to get a good estimate of transportation costs and logistics performance. This is because the small nuances in different scenarios cannot be adequately expressed in location-allocation models; hence, the need for detailed operational routes. The problem resembles a unique multiple logistics service provider vehicle routing model with pick-up and delivery allowing alternative delivery locations and with small vehicle capacity (namely two containers). This 2-container collection problem has not yet, to the best of our knowledge, been described in the literature. The next section provides a formal description of the problem.

6.2 The 2-container collection problem

The 2-container collection problem consists of a set of ELV-dismantlers, a set of depots, owned by an LSP and a set of recyclers. Distance and travel times between all locations are known. Both ELV-dismantlers and depots can initiate transportation orders for containers. Orders are planned periodically; we call the intermediate time the planning period. At an ELV-dismantler, empty containers are exchanged for full ones, while at a recycling facility full containers are exchanged for empty ones of the same type. Since a shortage of containers never occurs in practice, the depot locations are assumed to have sufficient storage for all container types for exchange purposes. Orders may be for either one or two containers; all orders concern containers of the same type. Full containers coming from ELV-dismantlers can be delivered either to a depot or to a recycling facility; full containers coming from a depot can only be delivered to a recycling facility. Which delivery location is selected depends on policy, practical restrictions, the estimated gate fee for dropping the order at the location and the logistics costs of including the delivery location in the route. The gate fee is the tariff charged by the recycling facility per unit material for processing, and depends on the residual value of the product. This fee can even be negative, i.e. money is paid by the recycler to acquire the material. Figure 6.2 provides a conceptual mapping of the problem.

A vehicle's route starts and ends at a depot. A route may take no longer than nine hours, of which one hour is overtime for a 50% higher rate. Each stop incurs both a fixed stopping time and a variable loading and unloading time. The costs of a route are composed of a distance and a time component. The model allows for differentiating the kilometer and hourly rates per LSP. Vehicle capacity in the model is limited to two containers. Each LSP is assumed to have an unlimited number of vehicles. This is realistic since these types of trucks are widely used. The next section explores the relevant literature dealing with similar problems.

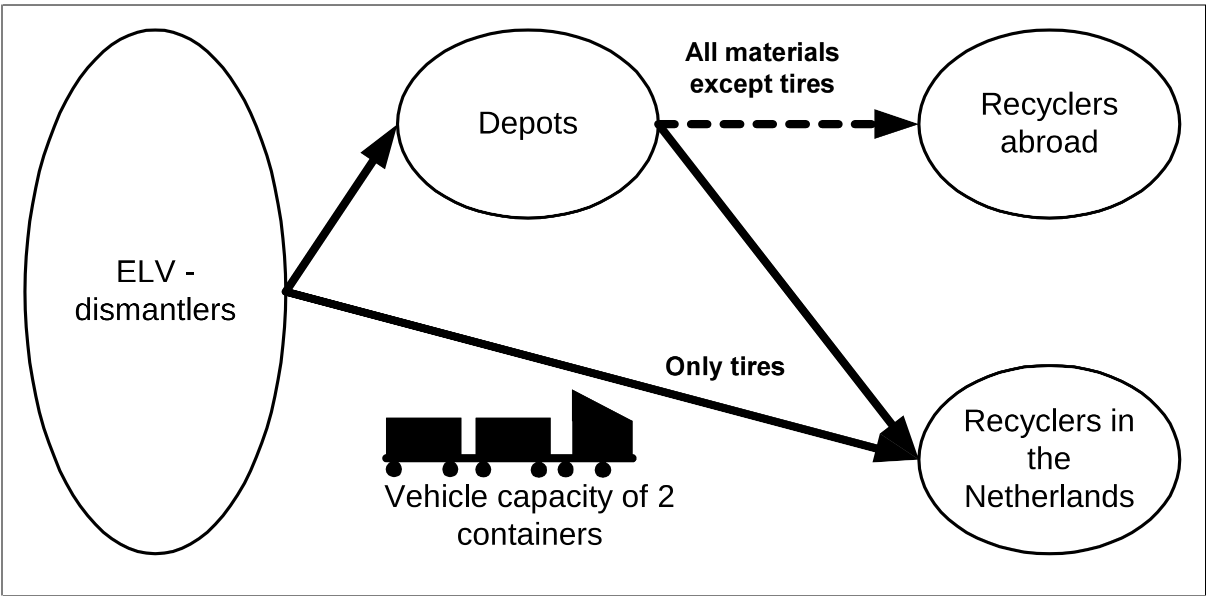

Figure 6.2. Conceptual overview of the collection problem.

6.3 Literature

The literature on vehicle routing is abundant, see Bodin et al. (1983) and Toth and Vigo (2002) for overviews. In reverse supply chains, variants of the classical vehicle routing problem occur that have been less extensively studied (Dethloff 2001). Beullens (2001) provides an excellent overview of vehicle routing models and the special types of models occurring in reverse logistics. In this section, we restrict ourselves to the literature describing problems with characteristics similar to the case at hand.

6.3.1 Related models in the literature

The problem closest to the situation at hand is the skip problem (SP) as described in De Meulemeester et al. (1997). Vehicles start at a depot and have to deliver empty skips to customers, collect full skips from customers, and deliver the full skips to either the depot or one of the disposal facilities. A vehicle has the capacity to carry one skip at a time. Skips can be of multiple types, and this presents a restriction in exchanging full for empty. De Meulemeester et al. (1997) develop two heuristics and an exact procedure for solving this real-life problem. The exact procedure is based on enumeration. The first heuristic is based on the classical Clarke and Wright savings heuristic. The second calculates a solution to a formulated transportation problem, providing a lower bound to the optimal solution. The solution to the transportation problem is made feasible in a number of heuristic steps. On average, the variant of the Clarke and Wright savings algorithm performed the best.

Bodin et al. (2000) describe a variant of the skip problem called the rollon-rolloff vehicle routing problem (RRVRP). In a RRVRP trip, a truck with a capacity for one container departs from a depot to serve customers who need a container placed, collected or exchanged (full for empty). The network consists of only one depot and one disposal facility, and all containers are of the same type. In that sense, the model of Bodin et al. (2000) is a simplification of the real-life case of De Meulemeester et al. (1997). Bodin et al. (2000) develop four types of algorithms. The first is again an adaptation of the Clarke and Wright heuristic. The second is a trip insertion and trip improvement heuristic. The third is a so-called decomposition algorithm, which starts by enumerating routes, and then solves a set covering problem. The resulting solution is improved with some swaps. The final and most advanced algorithm is a truncated dynamic programming heuristic, generating partial solutions that are completed by adding the non-covered orders by solving a bin-packing model. The contribution of Bodin et al. (2000) is of a theoretical nature, since they only test the heuristics using a set of randomly generated instances. The dynamic programming algorithm performs the best, although calculation times are long. The other algorithms are faster, but the trip insertion and trip improvement heuristics, in particular, are not competitive in terms of solution quality.

Archetti and Speranza (2004) describe another variant of the problem, the so-called 1-skip collection problem (1-SCP). As the name indicates, vehicle capacity is limited to one skip or container. Since Archetti and Speranza deal with a real-life problem, they consider several practical restrictions, such as multiple container types, time windows, different priorities for different customers and a limited fleet size. They develop a three-phase algorithm. In phase 1, the set of skips that needs to be collected that day is determined and ranked in priority. In phase 2, a solution for the subset of skips is constructed. In phase 3, the solution is further improved by using local search procedures.

6.3.2 Positioning our approach in the literature

Some of the models described in literature come close to the situation at hand, but none has the same characteristics. All of these models consider the vehicle capacity to be limited to precisely one skip or container, instead of two, as in our case.

Extending the algorithms described in the literature to the situation with two containers is not trivial. Techniques known from more general vehicle routing models could be considered; these techniques do not, however, exploit the discrete capacity of only two containers. The next section thus presents a new heuristic for tackling this problem.

6.4 Methodology

In order to handle our case-based problem, we developed a two-step heuristic. In the first step, a large number of candidate routes are generated. In the second step, a combination of routes is selected, minimizing the costs of drawing up a complete route plan, while satisfying all the requirements. This combination of route generation and set partitioning is referred to in the vehicle routing literature as the set partitioning approach, see for example Fleuren (1988). This specific type of algorithms where a promising set of possibilities is generated and a solution is found by set partitioning, is referred to as a petal algorithm (Laporte et al. 2000). An alternative way of applying set partitioning in this setting is by using column generation, see, for example, Agarwal et al. (1989). Since we have the rapid set partitioning solver of Van Krieken et al. (2004) at our disposal, and our average number of orders per route is limited, we chose to do an enumeration of a large set of feasible routes. Figure 6.3 depicts an overview of the heuristic.

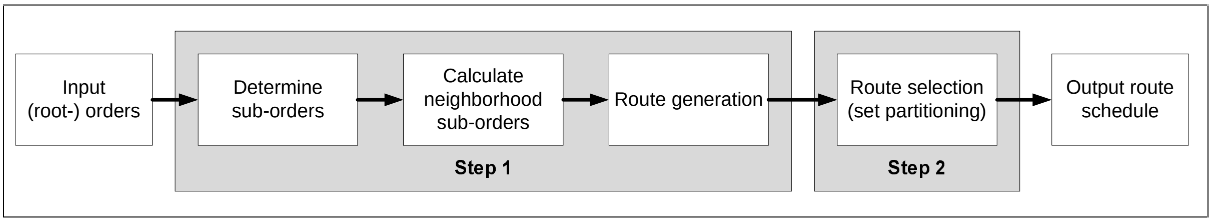

Figure 6.3. The framework for the routing heuristic.

6.4.1 Route generation

The purpose of route generation is to construct a set of feasible routes, such that the route selection procedure can make a “good” choice from the set. To tackle this multi-depot pick-up and delivery problem with alternative delivery locations, we introduce the concept of root-orders and sub-orders, described in Section 6.4.1.1.
Because the number of feasible routes grows exponentially, we suffice with the generation of a promising subset of routes. To restrict the number of candidate routes generated, we use the concept of order neighborhoods; this is the topic of Section 6.4.1.2. Finally, the route generation procedure is described in Section 6.4.1.3.

6.4.1.1 Root and sub-orders

To handle the pick-up and delivery problem with alternative delivery locations and selection of logistics service providers, we distinguish root- and sub-orders. Every transportation order has a general root-order with location- and LSP-specific sub-orders. Since each sub-order has a unique pick-up and delivery location as well as a logistics service provider, our algorithm can proceed along the same lines as a standard pick-up and delivery heuristic. To ensure that only one sub-order is performed per root-order, however, we have to add some constraints. We will motivate this with an example.

<u>Example on the use of sub-orders</u>

ELV-dismantler WreckRec has a container of tires that needs to be transported either to the tire recycler TireRec or to a depot of a logistics service provider. There are two competing logistics service providers with a depot: LogOpt and LogCheap. This single root-order results in four sub-orders as shown in Table 6.1.

Table 6.1. The sub-orders in the example of WreckRec.

Sub-order	LSP performing the order	Pick-up location	Delivery location
1	LogOpt	WreckRec	LogOpt
2	LogOpt	WreckRec	TireRec
3	LogCheap	WreckRec	LogOpt
4	LogCheap	WreckRec	TireRec

If a sub-order is selected with delivery to the depot, where delivery to the recycler was also an option, we have to correct the route costs for the future transportation costs from the depot to a recycler. In this situation, the sub-order generates a new root-order in the next planning period for the transport to the recycler. Since planning periods are short, three working days, this heuristic step is not a severe limitation. These costs are estimated using the equation [6.1].

$$\mathrm{CostCor}_{so} = \alpha \cdot \mathrm{LHC}_{so} \cdot \mathrm{Load}_{so} \qquad [6.1]$$

where:

α = Correction factor between ½ and 1

LHC_{so} = Linehaul costs to deliver a container from the depot of sub-order so to the cheapest recycler in transportation costs and gate fee.

Load_{so} = Number of containers in sub-order so

The correction factor α expresses the combination possibilities for the transportation orders from depot to recycler. If $\alpha = 1$, no combinations are made and the full linehaul costs are charged to collect a single container. The perfect combination would be two containers from the depot to the recycler, and two containers from an ELV-dismantler adjacent to the recycler back to the depot, which corresponds with α = ¼. In our implementation, we use $\alpha = 0.8$. We determined the value using historical data from ARN.

6.4.1.2 Neighborhoods

Because the total number of feasible routes can be very large, up to several million, we use the concept of neighborhoods to limit the set of candidate routes. Every order has a set of neighbors, ordered on a distance-based criterion. When we add orders to a route, we consider only orders that are in the neighborhood of the route, which is the union of neighborhoods of the orders in that route.

Formally, we can describe this as follows. At the start of an empty route, every sub-order can be inserted. Since we develop a set of routes, each root-order can occur on several routes. For each sub-order we define a set of neighboring sub-orders belonging to different root-orders. Let nb_subord_{so} denote this set of neighboring sub-orders for sub-order so. $RouteSubOrders_r$ denotes the set of suborders in route r. The neighborhood of a route r, denoted as nb_route_r, is the union of the neighborhoods of the sub-orders in a route, equation [6.2].

$$nb\_route_r = \bigcup_{so \in RouteSubOrd_r} nb\_subord_{so} \qquad [6.2]$$

To determine the neighborhood of a sub-order, we need a distance measure. This is a heuristic step in the procedure. Consider two sub-orders so_A and so_B, with p_{so} and d_{so} denoting the respective pick-up and delivery locations of sub-order so. Our distance measure is based on the best way to combine two orders rather than drive them separately. Mathematically, this criterion is given in [6.3].

$$\begin{aligned} dist_{so\_A,so\_B} = \min\{ & d(p_{so\_A}, d_{so\_A}) + d(d_{so\_A}, p_{so\_B}) + d(p_{so\_B}, d_{so\_B}), \\ & d(p_{so\_A}, p_{so\_B}) + d(p_{so\_B}, d_{so\_A}) + d(d_{so\_A}, d_{so\_B}), \\ & d(p_{so\_A}, p_{so\_B}) + d(p_{so\_B}, d_{so\_B}) + d(d_{so\_B}, d_{so\_A}), \\ & d(p_{so\_B}, d_{so\_B}) + d(d_{so\_B}, p_{so\_A}) + d(p_{so\_A}, d_{so\_A}), \\ & d(p_{so\_B}, p_{so\_A}) + d(p_{so\_A}, d_{so\_B}) + d(d_{so\_B}, d_{so\_A}), \\ & d(p_{so\_B}, p_{so\_A}) + d(p_{so\_A}, d_{so\_A}) + d(d_{so\_A}, d_{so\_B})\} \\ & - d(p_{so\_A}, d_{so\_A}) - d(p_{so\_B}, d_{so\_B}) \end{aligned} \qquad [6.3]$$

For each sub-order, we list the distances to all sub-orders belonging to a different root-order, and include the nearest nb_size sub-orders in nb_subord_{so}. Experiments with the required size of the neighborhood to find suitable solutions in acceptable computational time for the given study indicate that nb_size = 6 performs well. We will use this value. Figure 6.4 depicts the diminishing improvements found by extending the neighborhood size for a representative sample of 25 real-life instances, consisting of an average of 54 root-orders and 114 sub-orders. Further increasing the neighborhood size will marginally improve the solution and cause a big increase in the route generation times. Note that above a certain threshold value the route generation is no longer restricted, and all feasible combinations are generated.

Figure 6.4. The influence of changing the size of the neighborhood on the quality of the solution based on a representative sample of 25 real-life instances (computing time index 100 = 1498 s).

6.4.1.3 Outline of the route generation algorithm

The aim of the route generator is to create a large number of attractive and feasible routes. As stated in Section 6.4.1.2, we restrict the enumeration of routes by appending orders only from the neighborhood. A route is feasible if the maximum time allowed for one day and the maximum vehicle capacities along the route are not exceeded. Every time a full container is picked up from an ELV dismantler, it must be exchanged for an empty container of the same type. If this is not possible, the route is unfeasible. We make use of a recursive function implementation for the systematic generation of routes. The RouteGenerator function describes the main idea behind the route generation algorithm, see Figure 6.5.

A sub-order is added to a route by inserting the pick-up stop and the delivery stop of the sub-order in the route. Since we deal with the pick-up and delivery situation, for each possible position where the pick-up stop (StopP) can be inserted, we find the cheapest position to insert the delivery stop (StopD). The InsertSubOrder function describes the main ideas behind the insertion of a sub-order in a route, see Figure 6.6.

Although the number of routes generated is restricted by the size of the order neighborhood, it can still become very large in some cases. Occasionally, over 2.5 million routes are generated. In that case, memory limitations of our computers compel us to reduce the maximum allowed size of the neighborhood by one and to restart the route generation.

```
Function RouteGenerator

IF ( Route empty )
        RouteNeighborHood := Set of all SubOrders
ENDIF
FOR ( SubOrder in RouteNeighborHood AND RootOrder unplanned ) DO
        InsertSubOrder( SubOrder )
        UpdateRouteNeighborhood
        IF ( RouteFeasible ) THEN
                WriteRouteToRouteSelectionProblem
                RouteGenerator
        ENDIF
        RemoveSubOrder
        UpdateRouteNeighborhood
ENDFOR
```

Figure 6.5. Outline of route generation algorithm.

```
Function InsertSuborder( SubOrder )

FOR ( Position in Route ) DO
        Insert StopP
        FOR ( Position in Route after Stop P ) DO
                Insert StopD
                UpdateRoute
                IF ( BestInsertion AND RouteFeasible ) THEN
                        StoreBestInsertionPosition
                ENDIF
                Remove StopD
        ENDFOR
        Remove StopP
ENDFOR
IF ( BestInsertionExists ) THEN
        Insert StopD and StopP at best position
        UpdateRoute
ENDIF
```

Figure 6.6. Outline of the sub-order insertion function.

6.4.2 Route selection

The problem of finding the optimal combination of routes such that all orders are performed at minimal costs is formulated as a set partitioning problem. After introducing some notation, the problem is given in equations [6.4] to [6.6].

Parameters

$\delta_{so,ro}$ = 1 if sub-order so belongs to root-order ro, 0 otherwise.
$a_{so,r}$ = 1 if sub-order so is contained in route r, 0 otherwise.
c_r = denotes the costs of driving route r in euros.
p_r = denotes the profit or costs (negative p_r) of route r as a result of the chosen delivery locations for the orders in route r in euros.

Variables

X_r = 1 if route r is selected, 0 otherwise.

The route selection problem

$$\min \quad \sum_r (c_r - p_r) \cdot X_r \qquad [6.4]$$

$$\text{s.t.} \quad \sum_r \sum_{so} (\delta_{so,ro} \cdot a_{so,r}) \cdot X_r = 1 \qquad \forall ro \qquad [6.5]$$

$$X_r \in \{0,1\} \qquad \forall r \qquad [6.6]$$

Note that $\sum_{so} \delta_{so,ro} \cdot a_{so,r}$ is either 0 or 1 by construction of the route generator; the route selection problem is therefore a pure set partitioning problem. To exploit the special structure of the set partitioning problem we again make use of a special set partitioning solver developed by Van Krieken et al. (2004), rather than more generic mixed-integer linear programming solvers. Section 5.4.2 describes the main building blocks of the solver.

6.5 Structure of the analysis

6.5.1 Simulation

We use a simulation model to analyze the system's performance. The transportation orders from ELV-dismantlers are generated following empirical distributions. To obtain representative results, each simulation run consists of 10 replications of one year. In the simulation, the operational vehicle routing problem is solved twice a week for a planning horizon of three workdays. This means that over 1000 set partitioning problems are generated and solved per simulation run.
Orders generated during a period are planned for and executed in the next planning period. For containers of tires brought to the depot, the orders for shipping the containers to the recycler are also issued at the beginning of the next planning period. Transportation orders are thus fixed at the beginning of a planning period.

6.5.2 Data and scenarios

Data come from various sources. Distances and driving times used in the analysis were obtained from Evo-IT (www.evo-it.nl). The cost figures used were obtained from the NEA (2004), which is an authority on traffic and transportation issues in the Netherlands. We use cost prices rather than the commercial fees of individual LSPs. The input data used for simulating the processes at the ELV-dismantlers are empirical data retrieved from the corporate databases of ARN. A detailed description of these data can be found in Schreurs (2004).

The scenarios were constructed in cooperation with ARN logistics experts and the logistics service providers hired by ARN. Scenarios are defined along three dimensions:

- The lifting mechanisms used by the LSPs:
  - The current situation: two different lifting mechanisms are used
  - The ideal situation: all LSPs use the same standardized lifting mechanism
- The assignment of transportation orders to the logistics service providers:
  - Current fixed assignment: ELV dismantlers are assigned to LSPs and recyclers on the basis of provincial boundaries.
  - Optimized fixed assignment: ELV-dismantlers are assigned to the closest LSP/recycler based on a distance criterion.
  - Central planning: no fixed assignment exists; the LSP with the best combination possibilities executes the transportation order.
- The allowed routes for containers of tires:
  - No direct shipment: all tire containers pass the depot.
  - Direct shipment: this is allowed if it is advantageous to ship tire containers directly to a tire recycler instead of the depot.

Figure 6.7 shows six scenarios defined along the last two dimensions and their scenario IDs. These six scenarios can be applied to both of the lifting mechanisms, the first dimension, resulting in a total of twelve. Scenario Cur-indirect is our reference scenario, and corresponds to the current situation of ARN.

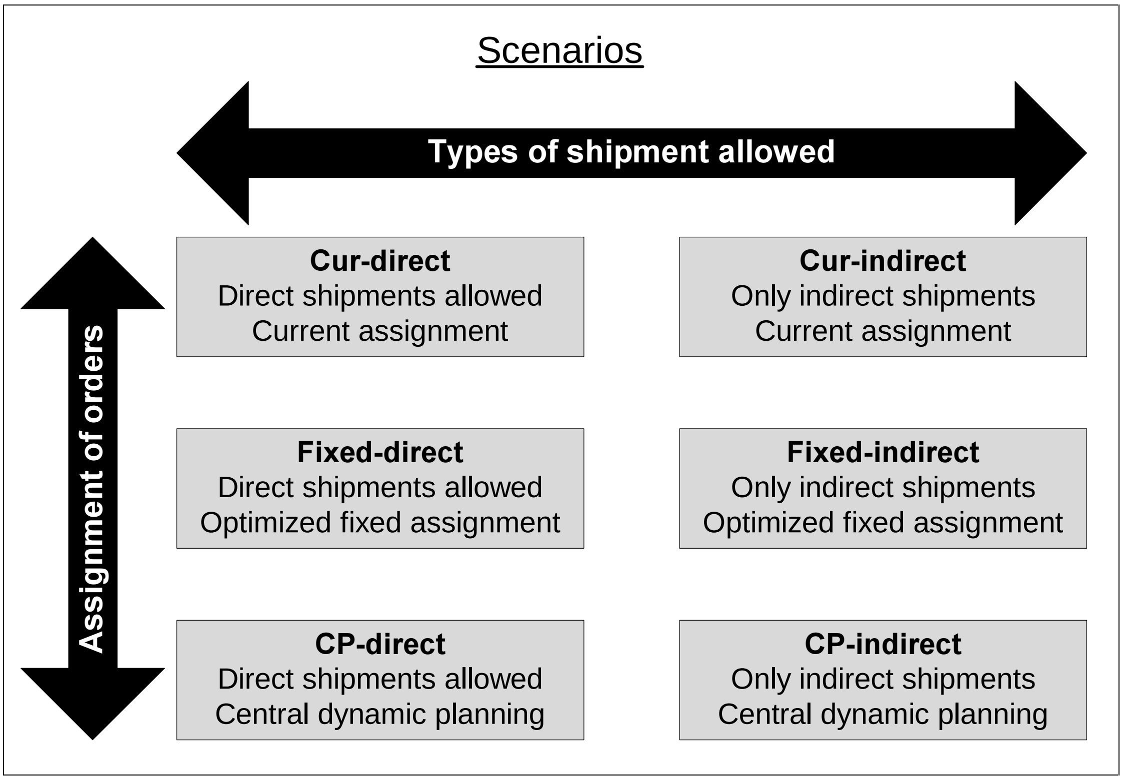

Figure 6.7. An overview of the scenarios.

The current assignment of ELV-dismantlers to depots and recyclers is based on provincial boundaries for historic reasons. This assignment is far from efficient in many cases, since some provinces in the Netherlands have irregular shapes. This is resolved by simply assigning each ELV-dismantler to the nearest depot with the proper lifting mechanism. The effect of a fixed assignment is analyzed in the central planning scenario by relaxing this constraint and using dynamic planning on a central level.

Currently, nearly all tire containers are transported to the recycler via a depot, since the container must be weighed at the depot. Since recyclers nowadays also have accurate weighing facilities for trucks, it is no longer necessary to make a stop at the depot.

6.6 Results

6.6.1 Network with current lifting mechanism

The results for the current logistics network with LSPs having different types of lifting mechanisms are presented in Table 6.2. For reasons of confidentiality, the cost figures have been indexed. A comparison with the other scenarios, as defined in Figure 6.7 for the yearly indexed costs, is also presented in Figure 6.8.

Allowing the logistics service providers to ship tire containers directly from ELV-dismantlers to recyclers results in cost savings ranging from 6.3% to 9.1%, depending on the way in which ELV-dismantlers are assigned to LSPs. The average route length increases both in time and distance, since it is more attractive to make a small detour to drop tire containers at a tire recycler rather than to bring them first to the depot and then to the recycler. This phenomenon is responsible for the drastic decreases in the number of routes driven, since most tire containers are now transported only once. Implementation of direct shipment is fairly easy and requires only some further arrangements with the recyclers.

Optimizing the assignment of ELV-dismantlers to depots and recyclers results in cost decreases ranging from 4.4% to 4.7%. This effect is small, since the diversity in container lifting mechanisms allows little freedom for optimization. It is fairly easy to change to another fixed assignment: it merely requires renegotiation of contracts with LSPs.

Compared to the optimal fixed assignment, the extra savings of dynamic allocation by central planning are limited, ranging from 0.6% to 3.6%. These marginal cost savings are not offset by the changes in the planning and control mechanisms to implement dynamic assignment.

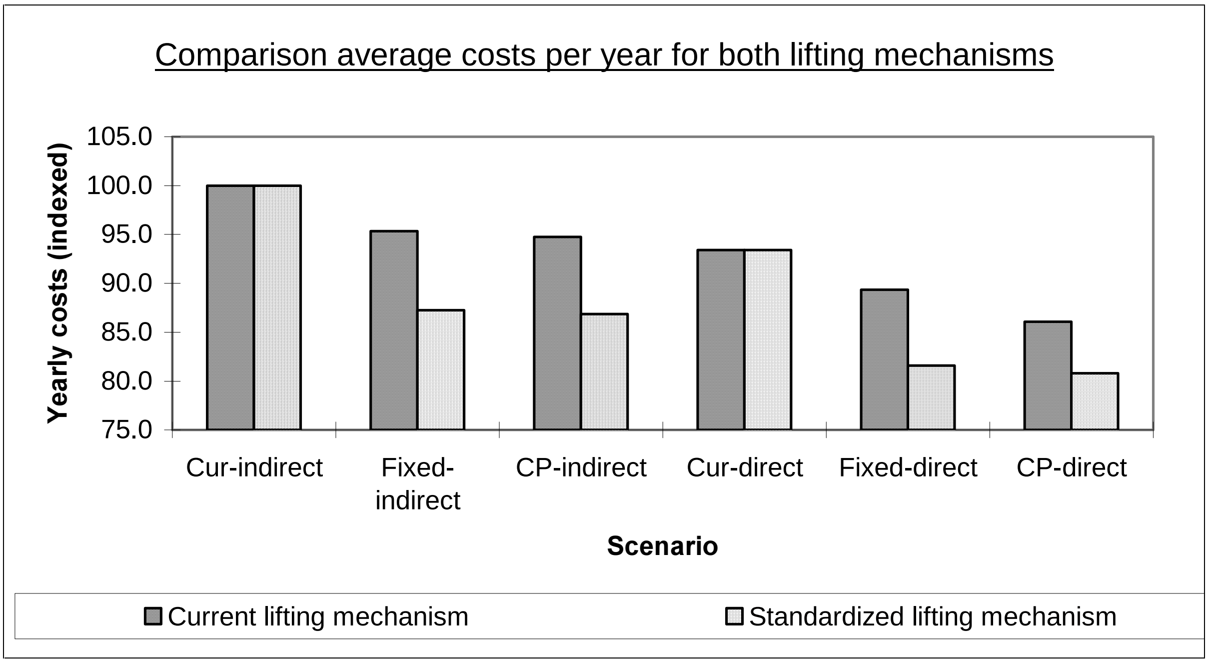

Figure 6.8. Comparison of scenarios with current and standardized lifting mechanism.

Table 6.2. Results for the current network with restrictions on the lifting mechanisms.

Scenario ID	Cur-indirect	Fixed-indirect	CP-indirect	Cur-direct	Fixed-direct	CP-direct
Assignment	Current	Fixed, optimized	Free, central planning	Current	Fixed, optimized	Free, central planning
Type of shipments for tires	Only indirect	Only indirect	Only indirect	Direct allowed	Direct allowed	Direct allowed
Average cost per year	100.0	95.3	94.8	93.4	89.3	86.1
Average distance per year (km)	505,779	471,610	467,188	483,092	458,972	433,735
Average number of routes per year	2,887	2,906	2,907	2,346	2,336	2,226
Average number of containers per route	2.45	2.44	2.44	2.39	2.32	2.42
Average route distance (km)	175.2	162.3	160.7	205.9	196.4	194.8
Average route duration (min)	291.0	277.6	276.1	331.3	319.7	325.4
Average driving time per route (min)	177.1	164.3	162.8	208.7	198.4	198.2
Average load and unloadtime per route	114.0	113.3	113.3	122.6	121.3	127.1

Table 6.3. Results for the current network after loosening the restrictions on the lifting mechanisms.

Scenario ID	Cur-indirect	Fixed-indirect	CP-indirect	Cur-direct	Fixed-direct	CP-direct
Assignment	Current	Fixed, optimized	Free, central planning	Current	Fixed, optimized	Free, central planning
Type of shipments for tires	Only indirect	Only indirect	Only indirect	Direct allowed	Direct allowed	Direct allowed
Average cost per year	100.0	87.2	86.9	93.4	81.6	80.8
Average distance per year (km)	505,779	411,893	408,954	483,092	402,125	394,886
Average number of routes per year	2,887	2,891	2,876	2,346	2,254	2,280
Average number of containers per route	2.45	2.45	2.47	2.39	2.39	2.36
Average route distance (km)	175.2	142.5	142.2	205.9	178.4	173.2
Average route duration (min)	291.0	258.8	259.4	331.3	306.6	301.1
Average driving time per route (min)	177.1	145.1	145.0	208.7	181.4	177.2
Average load and unloadtime per route	114.0	113.7	114.4	122.6	125.1	123.9

6.6.2 Network with uniform lifting mechanism for containers

The differences in lifting mechanisms in use by logistics service providers are likely to cause inefficiencies. ARN is lobbying for standardizing container lifting mechanisms at the LSPs. This situation is compared to the current situation in Table 6.3. Figure 6.8 shows the yearly indexed costs of the various scenarios for the current situation as well as for uniform lifting mechanisms. Currently, the assignment of dismantlers to depots and recyclers takes into account differences in lifting mechanisms. Therefore, standardization of the lifting mechanism makes sense only when the assignment is changed. We compare the current situation with the optimized assignment and central planning scenarios with a uniform lifting mechanism.

Using optimally fixed assignment, the cost savings of standardizing the lifting mechanism are about 8.7% when we allow direct shipments. If direct shipments are not allowed, the cost savings are 8.5%.

The cost savings of standardizing the lifting mechanism in the case of central dynamic planning are 8.3% when direct shipment is not allowed, and 6.1% when direct shipment is allowed. Given standardized lifting mechanisms, the cost savings of dynamically optimized central planning over optimized fixed assignment are less than 1%, whether or not we allow direct shipment, which does not offset the costs of the organizational changes. Standardizing the lifting mechanism is comparable with increasing the network density for the LSPs. Improving the combination possibilities in a dense network has a marginal effect on the costs since, in a dense network, there are already abundant combination possibilities. These results on central planning are supported by the findings of Cruijssen and Salomon (2004), who showed that the benefits of central planning are limited when orders are large compared to the vehicle capacity. Moreover, our orders are not randomly assigned to depots, but on the basis of provincial boundaries. Although provincial boundaries have shown to be far from optimal, they still have some logic and are much better than random assignment, as was initially the case in Cruijssen and Salomon (2004).

When we optimize the assignment of recyclers to LSPs, standardizing the lifting mechanism results in considerable cost savings that justify the necessary investment to implement this in the ARN chain.

6.7 In conclusion

This chapter described a case study in optimizing the logistics network for containers with materials coming from end-of-life vehicles. The underlying vehicle routing model is a unique multi-depot pick-up and delivery model with alternative delivery locations. The heuristic is based on generating a set of promising routes and selecting the optimal combination of routes by solving a set partitioning problem.

The managerial side concerns a better assignment of waste generators to logistics service providers and the impact of routing decisions made by central planning. Furthermore, we analyzed the influence of a policy that did not allow the direct shipment from waste generator sites to recycling facilities, and the effects of the different lifting mechanisms used for containers.

With respect to the assignment of recyclers to logistics service providers, we recommend changing the current fixed assignment, based on provincial boundaries, to an optimally fixed assignment. Considerable effort would be involved in implementation of the dynamic assignment option, while the additional savings over the optimally fixed assignment are limited. Since the study shows that allowing direct shipment will result in cost savings, and that the organizational burden is not very large, we recommend allowing direct shipment of tires to recyclers.

With respect to the lifting mechanism, the study has shown that standardization will result in significant cost savings, which makes it worthwhile to standardize the lifting mechanism in the ARN network. Compared to the current system, the total cost savings of the recommended new system, with standardized lifting mechanism combined with the option of direct shipments and the optimal fixed assignment, are over 18%.

The results of this study made ARN aware of the improvement possibilities. Together with the collection companies, ARN is currently investigating how to proceed with container collection.

Chapter 7

Towards new design principles

> *"Ik weet het niet. Het is mij vreemd te moede. Soms denk ik, dat ik weet wat het is; maar nee. Als ik dan even nadenk, weet ik het niet. Als je begrijpt wat ik bedoel."*
>
> *Olivier B. Bommel (3397)*

Chapter 1 introduced the field of closed-loop supply chains and the motivation for this research. We explained how the paradigm shift to life cycle management drives supply chain actors to close the loop. In Chapter 3, we used the logistics concept as framework to discuss both conceptual and modeling aspects of reverse supply chains. Our conceptual discussion focused on the determinants of reverse supply chains design, in particular the strategy determination and reverse supply chain network structures. Figure 7.1 repeats the logistics concept and the determinants. The logistics concept serves as a starting point for supply chain optimization using OR models. Our modeling discussion started with a broad description of the supply chain planning matrix for reverse supply chains, and later focused on the modeling of reverse supply chain network design. The theoretical framework of Chapter 3 was concluded by three propositions. Chapters 2, 4, 5 and 6 are concerned with the case studies and have a mainly descriptive character, i.e. they describe the problem solving approach. This represents the so-called regulative cycle in terms of Van Aken (1994), performing the typical steps involved in a real-life operations research project, as described by Fleuren (2001).

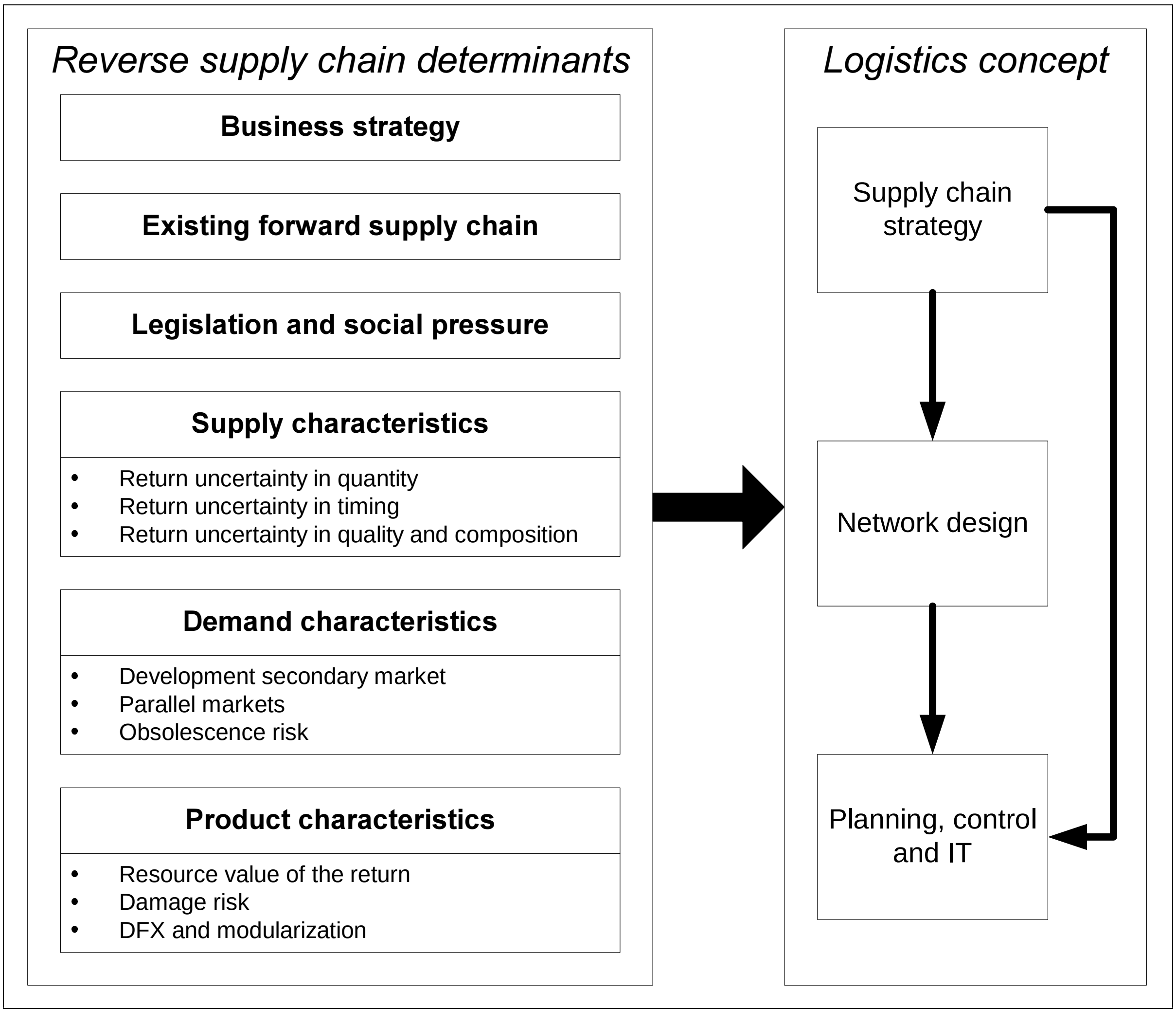

Figure 7.1. Typical reverse supply chain determinants and the logistics concept.

This chapter uses and interprets the knowledge gathered in the case studies to validate the propositions formulated at the end of Chapter 3. This is the so-called reflective cycle of Van Aken (1994). We sharpen the propositions and, where necessary, introduce complementary theory. For the sake of completeness, we repeat here the propositions stated at the end of Chapter 3.

Proposition 1

The closed-loop supply chain strategy can be based entirely on the value of the returned product and the time-dependency of that value. This captures the impact of all the considered determinants. The network design logically follows from the strategy. The matching reverse supply chain is either efficient, responsive, control or protection focused.

Proposition 2

A reverse supply chain should deal integrally with the full logistics concept; the current reverse supply chain design literature is too much concerned with its single *elements. Reverse network design exceeds location - allocation and should be based on the reverse supply chain strategy and interact with the lower level elements of the logistics concept.*

Proposition 3

The specific reverse supply chain determinants do not lead to special reverse supply chain design problems from an operations research point of view. Therefore, the development of special operations research models or algorithms for reverse supply chain network design is not justified.

Section 7.1 provides reflection on proposition 1. Based on this, we suggest that a theory extension is necessary, which is introduced in Section 7.2. Section 7.3 reflects on proposition 2, and Section 7.4 elaborates on proposition 3. The chapter concludes with an outlook to ongoing developments and further research in Section 7.5.

7.1 Which reverse supply chain strategy for which return?

This section positions the case studies of Chapters 4, 5 and 6 in the strategy framework of Section 3.4. The framework for determining the reverse supply chain strategy is based on two characteristics of a return. First, we consider the value of the return: either positive (economic) or negative (externalities). Second, we consider the time criticality of the value of the return. In this way, a total of four types of reverse supply chains are possible, focused on: efficiency, responsiveness, control or protection. We first describe the supply chain strategy of ARN. We then discuss and position the three cases in the framework, and evaluate whether or not the theoretical outcomes of the cases coincide with ARN's overall strategic intention. Finally, we revise proposition 1.

7.1.1 The supply chain strategy of Auto Recycling Nederland

The recycling network of ARN is set up by the automotive industry in reaction to legislation. Originally, ARN concentrated on activities that are not economically self-sustaining, but are required for compliance with the European Directive (Directive 2000/53/EC) on ELV recycling. The directive aims to minimize negative externalities by imposing processing requirements and recycling targets. For compliance reporting, control mechanisms are necessary. ARN fulfilled the requirements already in 1998. With the implementation of the European legislation, developments in other European countries accelerated. The automotive industry realized that ELVs have a positive residual value due to the metal content and spare parts. The expensive and solely control focused ARN network therefore has to make a shift towards efficiency. To ensure continuity of the system, ARN has made cost-cutting a strategic priority

(Auto Recycling Nederland, 2005). For the supply chain strategy of Auto Recycling Nederland, this implies the following:

- Improve efficiency of supply chain operations: supply chain optimization.
- Improve efficiency of dismantling operations by shifting from manual dismantling of materials to mechanical separation after shredding. ARN is developing plans to build a post-shredder residue sorting facility.
- Strengthen the control over hazardous materials and protect against liability by, for example, offering safe and environmentally sound systems for dismantling.

The business strategy as a determinant of the reverse supply chains impacts the reverse supply chain strategy. ARN must therefore move out of the control quadrant to the efficiency quadrant of our matrix. The consequences of this shift will be investigated in the following section.

7.1.2 Positioning the cases in the strategy framework

<u>Positioning the LPG-tank case (Chapter 4)</u>

In the situation prior to 2003, LPG-tanks were collected for degassing only in full storage racks on call of the ELV-dismantler. Collected LPG-tanks were degassed, i.e. the risk was neutralized, and then either traded or recycled to the material level by the degassing company. The time interval between collections in an on-call collection system was long, i.e. LPG-tanks were considered to be non-time-critical returns, despite the safety risk. Control over the safety risk was the focus of the system. However, some ELV-dismantlers traded LPG-tanks without proper treatment, ignoring the risk of remaining gas in the tank. These ELV-dismantlers positioned LPG-tanks as a positive valued time-independent product, thus requiring an efficient chain. Although trade in non-degassed LPG-tanks was not allowed, it occurred frequently; this was the major driver behind ARN to redesign the system and strengthen the control over the LPG-tanks. ARN wanted to “protect” itself against possible liabilities. Hence, a differentiation is made between degassed and non-degassed LPG-tanks, and the “old” situation twice in the strategy framework in Figure 7.2.

In the new collection system, the degassed LPG-tanks are periodically collected and returned to the ELV-dismantlers. The redesign considers the trade-off between collection of full storage racks in a low-density network, the old on-call collection system, and the collection of partly filled storage racks in a high-density network, the new periodic system. Overall, the periodic system is more costly, but the visiting frequency of the average ELV-dismantler increases from about 3-4 times per year to every 4 weeks. In this sense, ARN considers LPG-tanks as a time-critical product with negative externalities. Returning the degassed tanks within a few weeks after collection seems necessary in order to obtain the commitment of the ELV-dismantlers. After returning, the system is driven by the market. Hence, the new system before degassing can therefore be best positioned on the frontier between the control and the protection chain in Figure 7.2. This complies with the ARN strategy. After degassing, the LPG-tanks are non-time-critical spare parts that require an efficient chain. The main network consequences lie in the allocation of all LPG-tanks to the degassing facility and the introduction of a periodic routing system.

<u>Positioning the oil and coolant case (Chapter 5)</u>

Oil and coolant belong to the group of hazardous materials coming from ELVs. Removal and proper disposal are mandatory and must be proven to the law-enforcement representatives. In addition to the law-enforcement aspects, removal of these liquids is important to the shredders, to prevent contamination and damage to the shredder equipment. The introduction of storage tanks with telemetry improves the controllability, since the inventory levels can be observed at a distance. More important are the possibilities for changes in the logistics structure, in particular chain orchestration: ARN introduced the concept of collector managed inventory and proactive transportation planning. The logistics service provider has online information on the inventory levels and is responsible for timely collection of oil and coolant. ARN expects cost reductions of about 15%. Cost reduction was the main goal of this case. It illustrates the shift of the focus of the chain towards the efficiency quadrant, as shown in Figure 7.2. This is in accordance with the ARN strategy. The main consequence for the network lies in the change of control (orchestration) over the inventory from ELV-dismantlers to the LSPs.

<u>Positioning the container case (Chapter 6)</u>

In the container case, we compared various planning options for the transport of containers from the ELV-dismantlers to the recyclers. The intention of this study was to improve the efficiency of the overall system, keeping in mind that the logistics costs of the materials collected in the containers are among the highest in the ARN system. ARN expects to achieve a reduction on the logistics costs of about 15%. Control, which is a relatively minor issue for the materials collected in containers (tires, bumpers, PU foam, glass and rubber strips), is restricted to verifying the mass of the materials dismantled, transported and recycled. When relating the container case to the strategy framework, one recognizes a shift from the control focus towards an efficiency focus. This shift, illustrated in Figure 7.2, is in accordance with the ARN strategy. The main consequence for the network concerns the allocation of ELV-dismantlers to the LSPs.

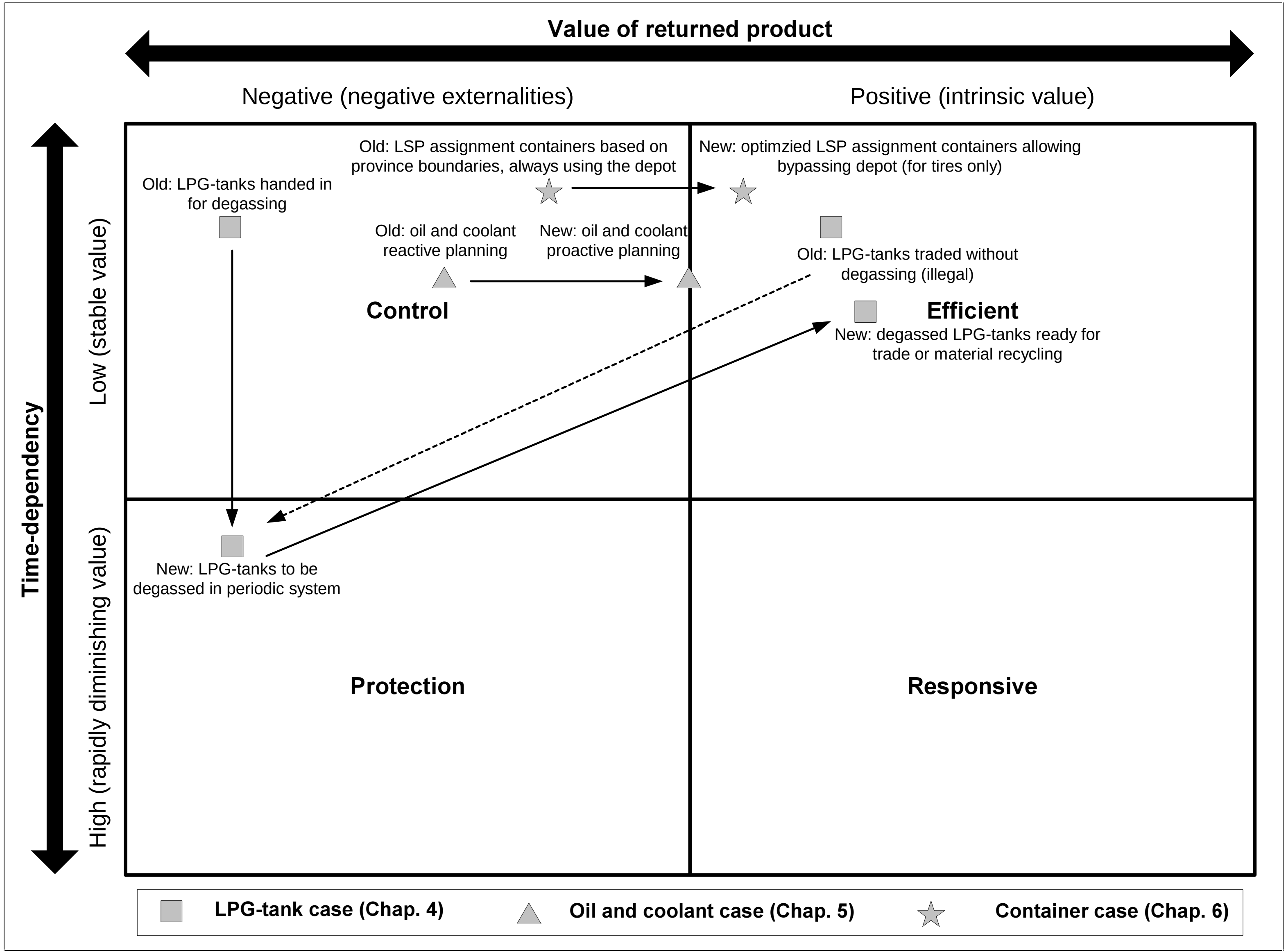

Figure 7.2. Positioning the cases in the strategy framework.

7.1.3 Reflection on proposition 1

This section reflects on and revises proposition 1 by interpreting the ARN case studies. Our value framework appears to be a useful tool for reviewing the reverse supply chain strategy. It clearly shows that the redesigned systems are moving along with ARN's new strategic intentions. ARN's current strategy is to be in or close to the quadrant of the control chain, but the developments in ELV-recycling will result in a strategic move of ARN from a purely control focused chain to a control-efficiency focused chain. Two of the three cases already indicate this gradual shift. Something remarkable is the case with respect to the LPG-tank case. The focus in this case is to close the leak flow of unsafe trade in LPG-tanks and protect against liabilities, indicating a shift towards a protection chain. On the other hand, once LPG-tanks are degassed they are valuable spare parts requiring an efficient chain. This is indicated by the double positioning of the LPG-tank case in the strategy framework of Figure 7.2.

Our strategy framework extends frameworks that are already known in the reverse supply chain literature. We conjecture that our framework is more generally applicable than just in the end-of-life area as defined in Section 1.6, because time and value are fundamental dimensions for all return types.

To a large extent, proposition 1 holds in the ARN cases. Questionable, however, is whether value and time-dependency of value capture all the determinants, in addition to the business strategy determinant that directly frames the reverse supply chain strategy. Once we examine the relationship between strategy and network design, the link of the supply chain strategy to all of the lower elements of the logistics concept seems weak, because we cannot derive the chosen changes in the network structure in the cases from the supply chain strategy alone. For example, the oil and coolant case and the container case both exhibit the shift from the control to the efficiency quadrant, however the changes in the network structure were totally different, hence other determinants must play a role. For instance, in the oil and coolant case, legislation is an important factor placing strict requirements on the processing and handling, while in the container case this is not an issue. Therefore, it is not possible to translate the strategy to the network design process straight away. It seems that some determinants directly impact the network design, while others are captured in the supply chain strategy and thus indirectly impact network design. Additional theory development on how the determinants impact the network design is necessary. Based on our ARN experience, we observe the following on the value and time dimension.

First, the value dimension of the returned product is critical to the required information on returns in the reverse supply chain. For positive valued returns, return information is important to determine the location, timing and the recovery option.

Once the return information is available, the decisions for the return are taken and the processes are value-driven. Considering the ARN network, some materials, e.g. bumpers, are valuable as spare parts and the information on the type and quality determines whether these are traded or handed in for material recycling. For negative valued returns, on the other hand, information on the (economic) value of the return is typically not important for determining the recovery option, since the goal is neutralizing the negative externality. In particular, information on the composition and toxicity of the returns and information related to mass balances are needed. However the information about timing, quantity and composition of the return can still be very useful to reduce costs. The value of inventory information in the oil and coolant case significantly reduced costs, although the recovery options are predetermined, similar to the container case. In conclusion, the degree to which information on the value of the return is available, influences the network design, since this determines the robustness of the network optimization. The type of information relates to the type of value.

Second, the time dimension influences the required span of control of the reverse supply chain over the return. Before control is obtained, processes are exogenous; after control is obtained, the processes are endogenous. For time-critical products, the point where control over the return is obtained should be located close to the disposer. For example, in the LPG-tank case we saw that ARN was eager to obtain all of the LPG-tanks for degassing due to the safety risk. In the new system, the LPG-tank is pulled to the degassing facility by providing a four-week service for degassing. For oil and coolant, the information on the availability of the fluids is shifted upstream by the use of advanced information technology. Large storage vessels reduce the time-criticality of oil and coolant, indicating an upstream shift of the decision-making responsibility. For the materials collected in containers, time-criticality is not an issue at all. In conclusion, the time dimension influences network design by positioning the points in the reverse supply chain where full control over the return is obtained.

Summarizing both dimensions: the point in the chain where control is obtained over the return and the point in the chain where the return information is available, influence the network design and ideally coincide at one point in the chain. This point separates the return-driven part of the chain from the value-driven part. To this end, we introduce the concept of decoupling points, similar to the theory known from the forward supply chain. In the next section we adapt the theory of decoupling points to reverse supply chains.

The proposition on the strategy part of the reverse logistics concept is modified to:

Proposition 1 revised
The closed-loop supply chain strategy can be based entirely on the value of the returned product and the time-dependency of that value. The matching reverse supply chain strategy is either efficient, responsive, control or protection focused. Next to the strategy, so-called direct determinants are the basis for network design. The relationship with network design must be worked out using decoupling point theory.

7.2 Decoupling points

This section introduces the concept of decoupling points for reverse supply chains to explain the link between the supply chain strategy and the network design. The determinants not captured in the value of the return, and henceforth in the reverse supply chain strategy, are expected to influence network design via decoupling points.
Although we assume the forward supply chain to be given, we find it useful to depict a holistic picture of closed-loop supply chains in view of decoupling points. In closed-loop supply chains one can basically distinguish two types of decoupling points.

1. The “classical” customer order decoupling point disconnects the order-driven part of the forward supply chain from the efficiency or process-driven part.
2. The disposition or disposer decoupling point (DDP) disconnects the disposer- or return-driven part of the reverse supply chain from the value-driven part.

The customer order decoupling point is well described and discussed in the literature, see, for example, Hoekstra and Romme (1994) and Olhager (2003). We briefly discuss the customer order decoupling point before we discuss the decoupling point in the reverse supply chain. The decoupling point is a linking element between the supply chain strategy and network design.

7.2.1 Customer order decoupling point in forward supply chains

The customer order decoupling point (CODP) indicates how deep the customer order penetrates into the supply chain, and divides the supply chain into two parts: a demand-driven part and a supply-driven part (Hoekstra and Romme, 1994). The CODP is also referred to as the pull-push boundary. Downstream of the CODP, the supply chain is provided with order information on a customer level, and processes are demand-driven. Processes are organized for flexibility, allowing quick response to customer orders. Upstream of the CODP, the supply chain is supply-driven to achieve economies of scale in the procurement, manufacturing and distribution processes. It exploits the ability of standardized mass produced components that are assembled into customized products later on.

Basically, the planning of the upstream part of the supply chain is fed with forecast information, whereas the downstream part is pulled by individual customer orders. The CODP is therefore the point in the supply chain at which demand uncertainty enters the supply chain. In general, the CODP coincides with a main inventory point in the chain to cover the uncertainty. The literature distinguishes five different CODP, see also Figure 7.3:

- Make to stock (MTS): the supply chain has a decentralized inventory of finished goods waiting for customer demand.
- Pack and ship to order (PTO): the supply chain has a centralized inventory of finished goods waiting to be sent for fulfillment of customer demand.
- Assembly to order (ATO): the supply chain produces a standard subsystem to stock; when the customer order arrives, the final product is assembled from the standard subsystem.
- Make to order (MTO): the supply chain keeps raw material and components in stock, and the final product is manufactured when the order arrives.
- Engineer to order (ETO): the supply chain keeps nothing in stock; the customer order is regarded as an engineering project.

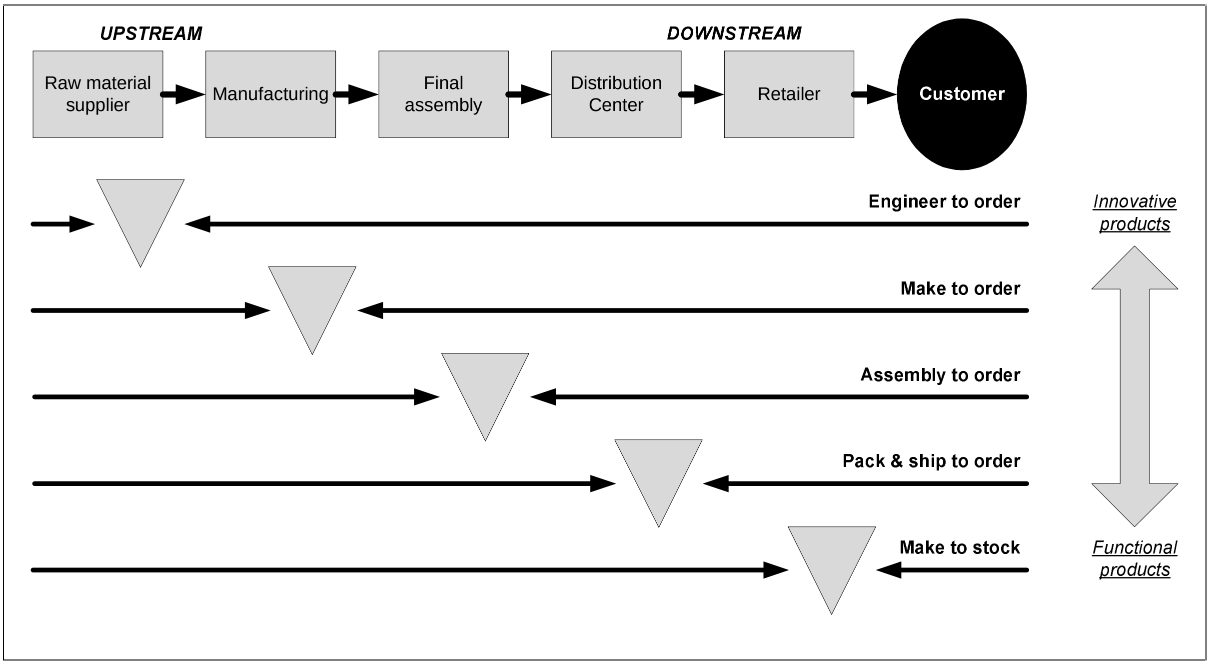

Figure 7.3. Customer order decoupling points in the supply chain, based on Hoekstra and Romme (1994).

7.2.2 Disposer decoupling point

The decoupling point is a fundamental concept for obtaining control of a flow of goods. The right positioning is a critical element in making the supply chain simultaneously lean and agile (Naylor et al., 1999). To the best of our knowledge, reverse logistics literature pays no attention to this concept. We find it remarkable, as it appears worthwhile to apply decoupling point theory to reverse supply chains. By logical deduction we introduce the disposition or disposer decoupling point (DDP), which indicates where the disposer is decoupled from the return, and from where the return is at the control of the reverse supply chain. The DDP separates the push or return-driven part from the pull or value-driven part of the reverse supply chain. We define the DDP as "*the point in the reverse supply chain where the disposition route can be actively managed*". It involves four critical decisions:

1. the recovery option
2. the location of recovery
3. the timing of recovery
4. the volume of recovery

The right positioning of the DDP seems critical in every reverse supply chain. For clarity, we define downstream in the reverse supply chain as close to the disposer, while upstream means far from the disposer, but close to the market of the recovered product. Placing the DDP too far downstream can make processes expensive, because too much effort is made during the acquisition and collection process to pull the return into the chain actively. For example, disposable cameras as described by Guide and Van Wassenhove (2003a) are decoupled upstream. The effort in collection and acquisition is limited, since the return of the camera is of direct interest to the disposer, because it still contains the film that needs processing. Positioning the DDP too far upstream can result in losing the value of the returned product, since the time elapsed until the disposition decision is taken is long, and insufficient information from the former user is captured. For example, in commercial returns of goods sold by catalogue or internet mail retailers, the decoupling is typically positioned shortly after the acquisition and collection phase. De Brito and De Koster (2004) describe the case of the return handling process at Wehkamp, a large Dutch mail-order company. The consumer can return goods free-of-charge within a number of days after purchase; according to De Brito and De Koster (2004) on average 28% are returned. As soon as a customer indicates the intention to return a product, the catalogue retailer is in charge of taking the product back. The returned goods are checked as soon as possible in the return channel in order to optimize the disposition route. Clothing, for example, is immediately checked for stains, and reconditioned by ironing and steaming, to prepare them again for shipment.

The use of advanced technology such as datalogs and installed base management systems can help in shifting the position of the decoupling point. Product uncertainty can be reduced, since information is captured in datalogs in the product (Klausner et al., 1998) or stored in installed base information systems (Van Nunen and Zuidwijk, 2004). This information allows the DDP to be shifted upstream, since almost immediately after collection, the right disposition and the routing through the reverse supply chain can be determined. A similar example of advanced information technology is discussed in the oil and coolant case in Chapter 5, where information on inventory levels is shared, resulting in an upstream shift of responsibility.

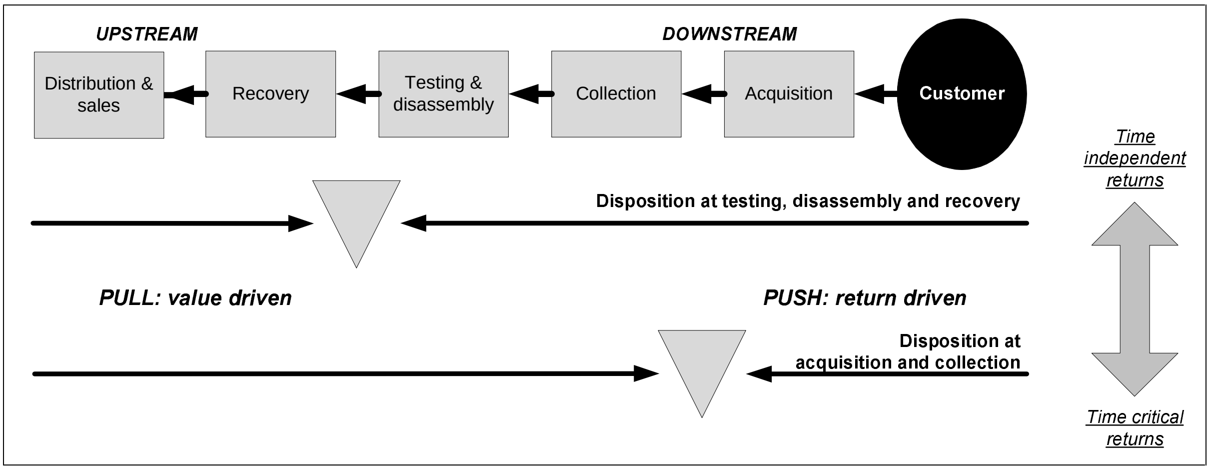

Figure 7.4. Disposer decoupling points in reverse supply chains.

In theory, the DDP could be positioned anywhere in the reverse supply chain. In reality, practical constraints and logical clustering of processes, e.g. testing and disassembly, reduce the number of options. We therefore propose two types of decoupling points in reverse supply chains, see also Figure 7.4:

- Disposition at acquisition and collection (DAC): The reverse supply chain actively initiates processes during the acquisition and collection process. After acquisition and collection, control is obtained and the disposition route is organized from top to tail.
- Disposition at testing, disassembly and recovery (DTR): The reverse supply chain obtains control and product information on the return during the testing, disassembly and recovery of the product. The reverse supply chain remains passive until the disposer pushes the return through the chain.

In Section 7.1.3 we presumed the existence of the DDP based on our experience in the cases. For the sake of clarity we show the position of the DDP in the ARN case studies in Figure 7.5. Next, we aim to connect the strategy and the network structure with each other.

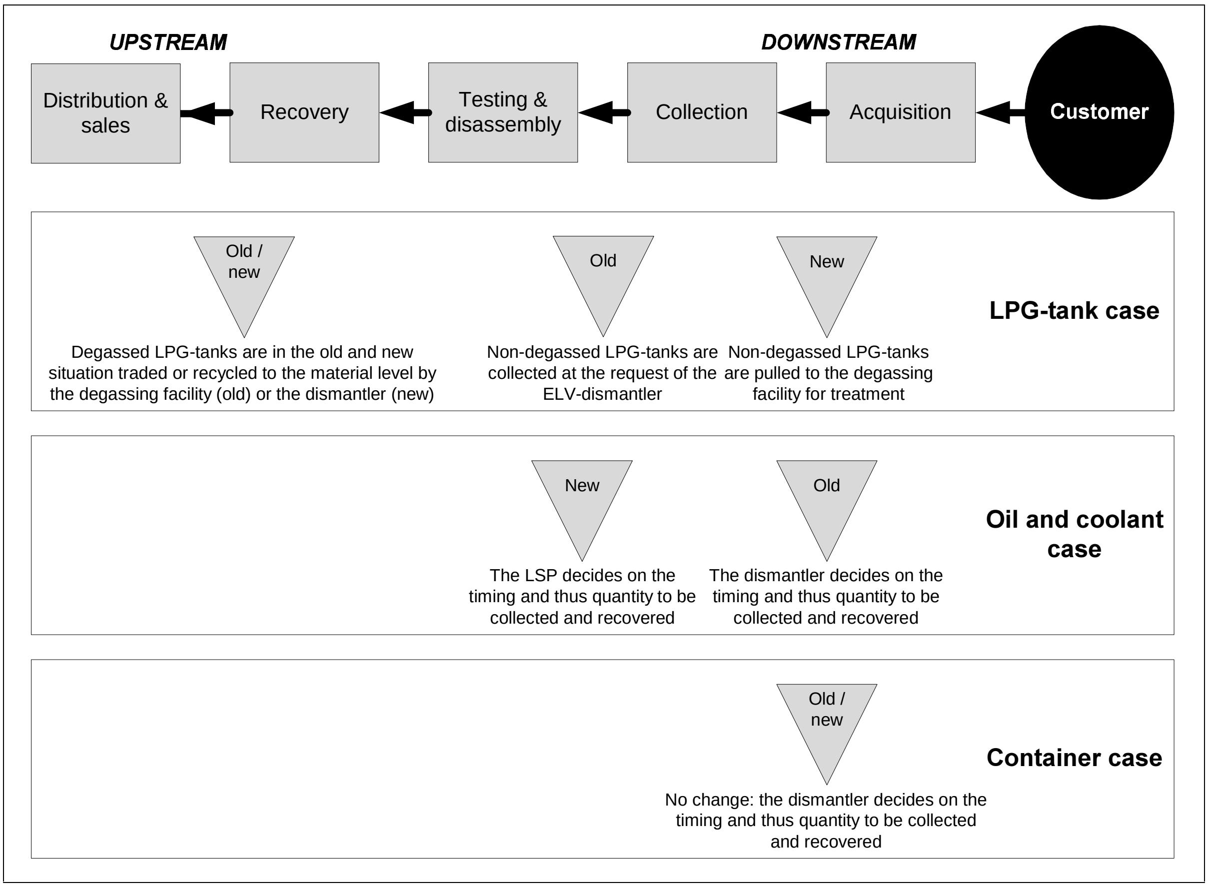

Figure 7.5. Positioning the DDP in the ARN case studies.

7.2.3 Linking supply chain strategy and network structure

In forward supply chains, the customer order decoupling point implicitly reflects the strategy framework of Fisher (1997) or the demand uncertainty part of the framework of Lee (2002). Functional products, which require an efficient chain, or perhaps a risk-hedging chain in terms of Lee, have a decoupling point located downstream. Innovative products, which require a responsive chain, or perhaps an agile chain in terms of Lee, have a decoupling point located upstream. In this way, the customer order decoupling point links the supply chain strategy to the network structure.

Similarly, the disposer decoupling point allows us to link the reverse supply chain strategy framework to the network structure. For the time dimension this is pretty straightforward. Returns having a stable value, either positive, requiring an efficient chain, or negative, requiring a control chain, have a decoupling point located upstream. Returns with a high marginal value of time, either positive, requiring a responsive chain, or negative, requiring a protection chain, have a decoupling point located downstream.

The value dimension is related to the availability, the type and importance of return information. The information aspect is related to the determinants of the reverse supply chains. The determinants of supply, demand and product characteristics in particular, influence the positioning of the decoupling point in the information dimension, because this information is needed for the four above mentioned decisions of the DDP. However, the role of information on the positioning of the DDP is not as unambiguous as is the case for the time dimension. The other determinants, the existing forward supply chain and legislation and social pressure, do not directly influence the role of information and hence the positioning of the decoupling point. These determinants can be seen as constraints on the network design process.

Table 7.1. Influential determinants of the disposer decoupling point.

Influential determinants DDP	Explanation	Strategy framework dimension
Supply characteristics		
Uncertainty in quantity	High uncertainty in quantity can be reduced at a centralized level due to the law of large numbers and thus pushes the DDP upstream.	Value
Uncertainty in timing	High uncertainty in timing can be reduced at a centralized level due to the law of large numbers and thus pushes the DDP upstream.	Value
Uncertainty in quality and composition	High uncertainty in quality and composition can be reduced by early assessing the return and thus have a downstream effect on the DDP.	Value
Demand characteristics		
Development secondary market	The better developed the secondary markets are, the more important return information is for the disposition decision. This is a factor pushing the DDP downstream.	Value
Parallel markets	Information on the return for disposition to determine the right market is important. DDP effects can go both ways.	Value
Obsolescence risk	Early control and early disposition reduce the obsolescence risk: a downstream effect on the DDP.	Time
Product characteristics		
Resource value	High resource value makes acquiring the return and having information on the return important, and thus has a downstream effect.	Value
Damage risk	High damage risk requires early control, i.e. time critical, pushing the DDP downstream.	Time
DFX and modularization	DFX and modularization allow for easier and thus early disposition on the component level and have a downstream effect on the DDP.	Value
Note that: • Downstream implies close to the disposer, far from the reuse market. • Upstream implies close to the reuse market, far from the disposer.		

For reverse supply chains in which acquiring the return is relatively unimportant, i.e. protection chains due to damage risk, the information aspect is less important and the time dimension dominates. For other types of returns, the interaction between information and time determines the position of the DDP. Table 7.1 demonstrates and explains how supply, demand and product characteristics as determinants influence the position of the disposer decoupling point.
Table 7.2 illustrates this translation of supply chain strategy to the network structure based on the disposer decoupling point. At least in the time dimension, it provides clear guidelines for positioning the decoupling point and selecting a network typology. The importance of information depends on characteristics related to some of the typical reverse supply chain determinants.

Table 7.2. Linking reverse supply strategy to the network structure.

	Strategy focus in the reverse supply chain			
	Control	**Protection**	**Efficient**	**Responsive**
Time criticality	Low	High	Low	High
Value of return	Negative	Negative	Positive	Positive
Role of information	Medium	Low	Medium	High
Disposer decoupling point	Upstream: close to reuse market	Downstream: close to disposer	Upstream: close to reuse market	Downstream: close to disposer
Network typologies	Recycling or rework-recycling network	Service-repair, hybrid-remanufacturing or trade-repair network	Recycling, rework-recycling network, exchange network	Reverse distribution, hybrid-remanufacturing or trade-repair network

Reflection on the new theory

This section introduced the concept of disposer decoupling point, which is the reverse supply chain counterpart of the order decoupling point. In Section 7.1 we concluded that the strategy framework needs support in translating supply chain strategy into network design. We suggest that the decoupling points are a step forward in linking the supply chain strategy to the network structure. Time criticality has a direct one-to-one relation with the positioning of the DDP. The information related to the value of the return obviously impacts the positioning of the DDP, however the relation is less unambiguous. Beside the decoupling point, other determinants play a role on the network design in a direct way. Nevertheless, we think that decoupling point theory is a critical building block in the development of theory and ultimately design principles in reverse supply chains.
In the end, we see that both the literature and our logistics concept based approach are neither right nor wrong. The approaches described in the literature take the

typical reverse supply chain determinants to explain the reverse supply chain network design. Since reverse supply chain strategy is skipped, critical dimensions are missed. On the other hand, taking the supply chain strategy as the only starting point, as we do in this thesis, fails to capture all the determinants of the reverse supply chain network design. The introduction of decoupling point theory is a refinement for translating the strategy into reverse supply chain network design, albeit not all comprehensive. Some determinants, like legislation and existing forward supply chains, act directly as constraints on the reverse supply chain network design. Figure 7.6 provides an overview of how the reverse supply chain determinants influence the design of the logistics concept.

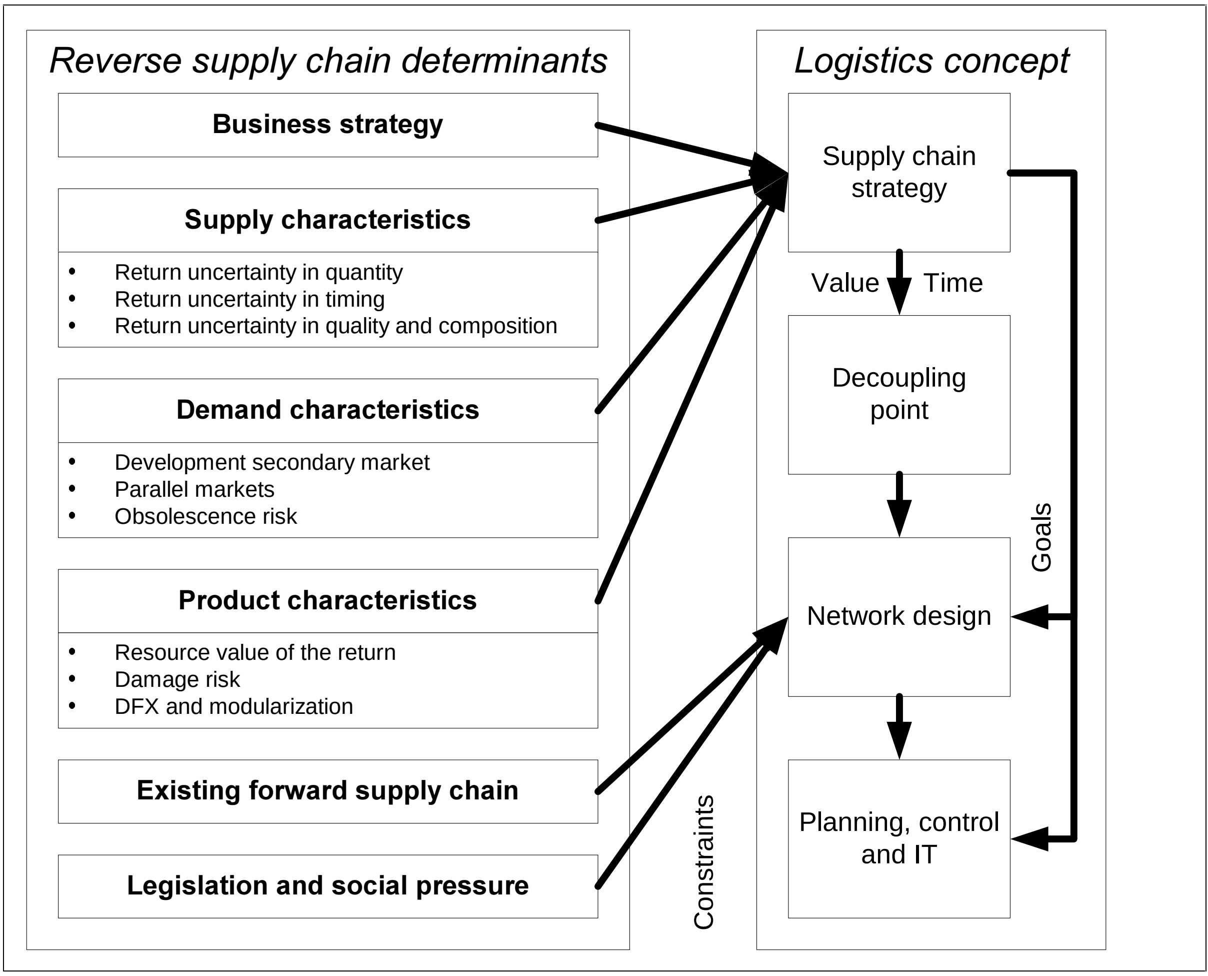

Figure 7.6. An overview of how the determinants interact with the logistics concept.

7.3 Considering the full logistics concept

This section reflects on proposition 2 using the case studies of Chapters 4, 5 and 6. The proposition deals with network design as an integral element of the logistics concept, for an overview of the logistics concept recall Figure 3.1.
The logistics concept encompasses strategy, network design and the planning, control and IT layer, because closing loops concerns closing the goods flows, information flows and markets (Krikke et al., 2004). Strategy, which was discussed in Section 7.1, sets the supply chain goals for network design. The focus on cost reduction is the clear driver in both the oil and coolant case and the container case, while for LPG-tanks the strategy is somewhat more diffuse. This section focuses on the interaction between network design and the planning, control and information infrastructure. In proposition 2 we explicitly stated that network design encompasses more than location – allocation decisions. Interaction with the other elements of the logistics concept is important. This was illustrated in Section 3.7.2 on the interaction of transportation planning with network design in both forward and reverse supply chains. Chain orchestration decisions in routing and inventory management, for example, are part of strategic network design. In the typical case in this thesis, considering end-of-life recycling chains, we cannot deny the importance of the interaction of transportation planning and network design. We illustrate this by discussing the interaction of network design and routing decisions in the case studies of Chapter 4, 5 and 6. Table 7.3 illustrates the importance of routing decisions in the case studies.

Table 7.3. The importance of routing in strategic network design in the case studies.

Case	**Network design aspect requiring routing**	**Consequence if it were omitted**
LPG-tank case (Chapter 4)	Estimation of transportation costs	• Bad cost estimations • Impossible to express the differences between: o Size of storage racks o Length of period
Oil and coolant case (Chapter 5)	To assess the value of inventory information for transportation planning	• Rough cost estimations
Container case (Chapter 6)	To assess the possible cost reductions by adopting alternative planning concepts	• Only a better assignment of ELV-dismantlers to LSPs and recyclers • No indications on the central planning scenarios • Rough cost estimations

The LPG-tank case (Chapter 4)

Incorporating routing aspects in the network design stage is essential in the LPG-tank case for a number of reasons. First, the differences in costs in the various scenarios, with differences in the size of the storage racks and the length of the planning period, are small, but in practice significant. Second, the synergies possible by combining various ELV-dismantlers in routes can best be estimated by solving the routing problem. Adopting the standard approach based on linehaul distances would omit the level of detail and therefore lead to results that are not accurate enough for management decision support.
Restricting the focus of the analysis on the location – allocation model would have helped in answering the question on the degassing strategy, central or regional, but would have ignored other details. The application of the vehicle routing model enabled us to answer the questions posed by ARN management to the full extent. Schultmann et al. (2004) came to a similar conclusion in a comparable case study.

The oil and coolant case (Chapter 5)

The oil and coolant case appraises the value of inventory information for transportation planning. The proposed alternative system, using telemetry and adopting a proactive planning methodology, considers a change of orchestration, i.e. a change of responsibilities. It is therefore a typical example of a network design issue not altering the physical network layout. The required investments and the change of relationships in the chain are long-term and can be considered as strategic decisions. Location – allocation models would not be capable of assessing the questions related to the case.

The container case (Chapter 6)

In the container case we compared the current assignment with a fixed optimized assignment and with a central planning scenario. In the fixed assignment a standard location – allocation model would suffice to analyze the assignment of ELV-dismantlers to logistics service providers and to recyclers. To assess the effects of a central planning scenario, we cannot use a location-allocation model, since assignments are no longer fixed but determined dynamically. A routing model is thus needed to determine the best combination of possibilities over the logistics service providers. Similar to the oil and coolant case, the physical network remains unchanged; the changes concern shifts in responsibility between LSPs and, in the case of central planning, a change in the chain orchestration to the central planning unit.

Reflection on proposition 2

Supply chain design should cover the full logistics concept, from strategy and network design to the planning and control layer. Strategy sets the overall goals for network design. In the literature, the strategy step is often not considered explicitly, but is assumed to be determined by the determinants in network design. Attention to (physical) network design in reverse supply chains has grown abundantly in the last 10 years. Remarkably enough, attention for the interaction with the planning and control elements of the logistics concept is limited. The attention is focused on the single elements of the logistics concept, such as inventory control and disassembly planning. In our case studies, we focus on the interaction of network design with routing or transportation planning. Most of the management questions in the ARN case studies could not have been answered appropriately if routing aspects were omitted. We therefore confirm, based on the cases, that network design encompasses more than location – allocation models. Attention in the literature to the interaction of network design and routing decisions is limited. In the past, special location-routing models have been developed in the general literature, but the applicability of these models is limited due to the complexity of the problem, the assumptions and the limited size of solvable models. Furthermore, we argue that strategic network design involves decisions that do not directly change the physical network structure, but change organizational aspects such as chain orchestration. The oil and coolant and the container case are typical examples, similar to the factory gate pricing example in forward supply chains we saw in Chapter 3.7.2.

Finally, the case studies indicate that the proposition holds for end-of-life management in a collective solution, executing the extended producer responsibility, for which ARN is a representative case. Validity in other domains may be possible, but further research is recommended. We state the proposition in its general form:

Proposition 2 revised

A reverse supply chain should deal integrally with the full logistics concept; the current reverse supply chain design literature is too much concerned with its single elements. Reverse network design exceeds location - allocation and should be based on the reverse supply chain strategy and interact with the lower level elements of the logistics concept. This requires combinations of models, e.g. location-routing and inventory routing models.

7.4 Operations research modeling consequences

In this section we reflect on proposition 3, dealing with the question whether or not the special reverse supply chain determinants require the development of new operations research models and algorithms for network design. We define a model as the mathematical description of the abstracted real-life problem, while an algorithm is defined as a sequence of processing steps to solve the model.
In the literature the special characteristics or determinants of reverse supply chains are often used to justify the development of new theory. In this research we follow the logistics concept of Van Goor et al. (1998) to discuss the impact of typical reverse supply chain determinants on strategy, network structure design and the planning, control and IT layer. From a modeling perspective we deal only with the network design level of the logistics concept. Models using MIP, LP and similar techniques seem to dominate, see our discussion in Section 3.7. Since we consider network design to encompass more than the physical network and to include decisions on chain orchestration, we extended the modeling scope beyond location-allocation models: routing models are a necessity. In each case study chapter we have incorporated a paragraph on the related literature. Each of the case studies we performed for ARN had some specific characteristics that are not captured by existing models and compelled us to modifications. The three cases are considered briefly below. For each case, Table 7.4 summarizes the justification of the adapted modeling, the modeling itself and the techniques used.

The LPG-tank case (Chapter 4)

The LPG-tank case was modeled as a standard location-allocation model with a separate vehicle routing model to feed the location-allocation model with accurate transportation cost estimations. Sensitivity analysis was used to analyze the effects of uncertainty in the parameters. Location-allocation models assume that the transportation cost parameters are known beforehand. Models in the literature explicitly dealing with routing, the location-routing models, or with uncertainty in parameters, the stochastic location models, are impracticable for the case due to reasons discussed in Section 4.3.
The way in which the case was modeled deviated from the classical approaches in the literature and has similarities to the approach described by Schultmann et al. (2004). The techniques used to solve the model are standard. The location-allocation model is solved using a commercial MILP solver. The vehicle routing model is based on a basic construction heuristic combined with local search for improvement of the solution.

Table 7.4. The case studies and the OR consequences.

Case	Shortcomings of the literature, justification for adaptations modeling	Modeling	Techniques used
LPG-tank case (Chapter 4)	• Stochastic models and location-routing models are computationally too complex for real-life cases. • Extensive data requirements. • The interdependency between operational effects of strategic decisions for this problem is not sufficiently expressed.	Strategic network design model with a separate vehicle routing model for making transportation cost estimations.	• Classical vehicle routing heuristics for construction (nearest neighbor) and local search for improvement. • Mathematical programming: a variant of the location-allocation model.
Oil and coolant case (Chapter 5)	• Time between two consecutive visits is relative short, days – weeks, instead of months as in the case. • Focus on balancing transportation and inventory costs instead of only efficiency in transportation as in the case. • Inventory levels are forecasted and not known, as is in the case with telemetry.	Simulation of processes including the transportation planning during a year with replications. The transportation planning is based on two types of transportation orders: must-orders and can-orders.	• Simulation. • Route generation. • Mathematical programming: set partitioning
Container case (Chapter 6)	• Generic models do not exploit the discrete vehicle capacity of two containers. • Specific models are limited to only one container.	Simulation of processes including the transportation planning during a year with replications. To model the multiple logistics service providers and delivery locations adaptations are made.	• Simulation. • Route generation with the use of neighborhoods. • Mathematical programming: set partitioning.

The oil and coolant case (Chapter 5)

The oil and coolant case has similarities with distribution problems of industrial gases and soft drinks in forward supply chains. In Section 5.3 we discussed the literature and concluded that our oil and coolant case has deviating characteristics justifying an alternative modeling approach. Especially the long time interval between the two collection visits and the irrelevance of inventory holding costs is typical for this case.
Our approach is based on a vehicle routing model with two types of transportation orders: can and must-orders, similar to the can-order inventory systems in forward supply chain theory (Silver et al., 1998). The resulting model is solved using standard techniques: route generation and route selection by solving set partitioning problems. This is referred to in the literature as a petal algorithm (Laporte et al., 2000). To analyze long-run performance, we used a simulation repeatedly generating transportation orders and solving the resulting planning problem.

The container case (Chapter 6)

The literature has described problems with characteristics very similar to those in the container case. Unfortunately, in these models the vehicle capacity is restricted to only one container. To cope with the ARN situation we needed to adapt the modeling and especially to extend the vehicle capacity to two containers. To solve the model we again use route generation and route selection by solving set partitioning problems. Simulation is used to assess the long-run performance of the various scenarios.

Reflection on proposition 3

It is often claimed that the special determinants of reverse supply chains justify the development of special OR models and algorithms for network design. In this thesis we discussed three cases concerning network design, and assessed both the modeling and the algorithmic requirements.
ARN’s physical network is constructed by contracting the ELV-dismantlers, the LSPs and the recyclers. The physical layout of the network is therefore not a location decision, but a sourcing decision for ARN. Only in the LPG-tank case, which represents a unique situation, since LPG-tank degassing in the Netherlands is only done by ARN, a location-allocation model is used. In the other cases the focus is more on better orchestration of the network. Since the costs of dismantling and recovery processes can be considered as exogenous, due to ARN’s need to comply with legislation, the focus is on transportation costs. In these models, this is reflected by the attention paid to the strategic use of vehicle routing models. Assessing the routing aspects is necessary in order to analyze the effects of strategic changes in the chain orchestration. The literature has described models with equivalent characteristics. However, none of the models in literature was capable of handling

the case at hand. We therefore had to adapt existing models to cope with the situation at hand. We used a combination of models for reverse supply chain network design to improve the analysis. The use of a combination of models is an implication from the revised proposition 2; the applied models are adaptations of standard models. In nearly every real-life project, adaptation to standard models is required to fit the problem at hand. This is not specific to reverse supply chains.

The approach chosen to solve the model resembles the choices of algorithms. Since we considered real-life problems, the instances are too large for using optimal solution-guaranteeing algorithms. The standard vehicle routing problem is known to be an NP-hard combinatorial optimization problem. Heuristics are used to find good but not necessarily optimal solutions. The choices we made for the heuristics represent our insights on what we considered to be robust algorithms for finding good solutions, while dealing with practical restrictions. Clear guidelines for selecting algorithms to solve a vehicle routing problem with specific characteristics do not exist, although the subject is considered in the literature, see Laporte et al. (2000) and Van Breedam (2002). The set of techniques we used to solve the problems are standard and described well in the literature: simulation, (mixed-) integer programming and route generation.

From an operations research perspective, we learn from the cases that models and algorithms are not essentially different between forward and reverse supply chains, although adaptations to the models are needed to fit the specific reverse supply chain problem. The determinants of the return influence the modeling of the reverse network design. Since adapted forms of classical models suffice, the need for special algorithms in network design seems limited. In situations, where new models or algorithms are necessary, we maintain that the situations are not specific for reverse supply chains alone, but also for forwards supply chain chains. For example, stochastic location-allocation models, as described by Listes and Dekker (2005), are not only of value for reverse supply chains with return uncertainty but also for forward supply chains with demand uncertainty. The developments of operations research models and algorithms in network design in forward and reverse supply chains should be merged.

We therefore retain the proposition stating that the special determinants of reverse supply chains alone do not justify the development of new operations research models and algorithms, although adaptations are nearly always required for specific situations (as is the case in forward supply chains):

Proposition 3 revised
The specific determinants of reverse supply chains do not lead to special supply chain design problems from an operations research point of view. Therefore, the development of special operations research models and algorithms is not justified, although the modeling needs to be adapted.

7.5 Concluding remarks

In this chapter we used the case studies for validation of the propositions formulated at the end of Chapter 3. The original propositions are based on the literature and theory on closed-loop supply chains. The three revised propositions are the refinement based on the experience during the case studies and are validated within the domain of the case studies. The revised propositions reflect our insights on the strategic design of reverse supply chains. In this section, we first demarcate the scope and then make some final remarks on reverse supply chain strategy, decoupling points, network design and network design modeling.

<u>Limitations: generalization and validity of the results</u>

This thesis aims at providing design principles for reverse supply chains. However, as a result of the methodology, the results are validated only within a small area in the field of closed-loop supply chains. The scope of this thesis is restricted to returns:

- of durable products in the end-of-life phase,
- where material recycling is the foremost recovery option,
- managed in collective systems,
- driven by environmental legislation setting strict recycling targets.

The scope corresponds to the situation of ARN, as described in Chapter 2. Similar systems occur more often in Europe, for example the European Recycling Platform and the NVMP, both managing waste electronic and electrical equipment (WEEE). Generalizations to other areas in the field of closed-loop supply chains seem possible, but more research is required.

<u>Reverse supply chain strategy</u>

We analyzed the impact of the typical reverse supply chain determinants on the design of reverse supply chains, following the hierarchical approach suggested by the logistics concept: strategy, network design and planning, control and information technology. In Chapter 3, we proposed a framework that seems to capture the impact of the determinants for strategy determination. The validity of the framework for the focal area is shown in this chapter. Wider applicability seems feasible, but more case studies are needed for validation.

Decoupling points in reverse supply chains

From our experience with the case studies, we recognized a gap in translating the strategy to the network design. In this chapter, we therefore developed some new theory and introduced the concept of the disposer decoupling point (DDP). The DDP is the point in the chain where the decisions on the recovery option, location, timing and volume of recovery are taken. We have illustrated that the decoupling point influences the network design in two dimensions:

- The time criticality of managing the return and obtaining control.
- The information availability, which in turn depends on value of the return.

Although the DDP clarifies the relation between the strategy and the network design, this relation is not unambiguous. Especially the information dimension influences the network design in multiple directions. Further research on the DDP for refinement of the concept, generalization and validation is necessary.

Reverse supply chain network design

In this thesis, we have furthermore shown that network design involves other aspects than location-allocation decisions. Interaction with elements of the planning, control and information technology layer is important. We focused on the interaction of network design with routing, since transportation costs are a large fraction of the total reverse supply chain costs in the networks studied in the focal area. Omitting the routing components in the cases would weaken the value of the analyses. We state that the interaction of network design with other elements of the logistics concept is important, not only on routing, but depending on the type of return, possibly with other planning processes. Further research to generalize to other planning processes and to extend the validity beyond the focal area is required.

Operations research consequences for reverse supply chain network design

From an operations research perspective on network design, we have seen in the literature review that the required models and algorithms are not essentially different from those used in forward supply chain management. This is supported by our case studies, where we saw that only the modeling needs adaptations. In the cases, we used a combination of well-known techniques to cope with the problems considered, since we broadened the scope beyond location-allocation analysis and included routing aspects. Adapted location-allocation models seem well applicable. The need for new models and algorithms in forward and reverse supply chains does not seem to be essentially different, and researchers in forward and reverse supply chain network design should join forces. Further research on whether this holds for other types of returns and for other planning processes in reverse supply chains is essential.

The next chapter concludes the thesis by providing an overview of the thesis, the contributions of our research and suggesting an outlook to the future.

Chapter 8

Conclusions

> *"Wanneer der wetenschap weet wat der toekomst brengen gaat, dan kan der wetenschap niet verder gaan. Het is niet wetenschappelijk om vooruit te kijken."*
>
> *Professor Prlwytzkofski (4535)*

8.1 Summary

This thesis provides a structured analysis of the elements of the reverse supply chain logistics concept, especially strategy and network design. With regard to network design, this is complemented by an analysis of the OR modeling consequences. Furthermore, a set of design principles has been formulated as propositions. Using a case study methodology, we have validated and refined these propositions within the defined boundaries.

Chapter 1

The thesis started in Chapter 1 with an introduction into the field of closed-loop supply chains. Closed-loop supply chains concern the extension of forward supply chains with a reverse supply chain thereby covering the product life cycle. The growing importance of closed-loop supply chains is driven by the scarcity of natural resources, the trend towards function selling and increased product liability. During the life cycle, various types of returns occur due to various reasons. This thesis focuses on the class of end-of-life returns, where the focus in the past has been (too) much on compliance with legislation and less on economical aspects. Especially in Europe, these returns are driven by extended producer responsibility legislation.

OEMs (original equipment manufacturers) are compelled to take the responsibility, ate least financially, for the environmental friendly disposal of products. The key issue is to find efficient solutions, both economically and ecologically.
We use a methodology based on the regulative and reflective cycle of Van Aken (1994) and case study research using the methodology of Yin (2003). In the regulative cycle, we study the literature on the logistics concept for reverse supply chains, resulting in the formulation of propositions. The case studies are part of the regulative cycle in terms of describing the problem solving approach from an operations research perspective. The reflective cycle uses the results from the case studies for validation and refinement of the propositions. The resulting propositions represent the practical design principles.

Chapter 2

Chapter 2 introduces the Dutch recycling system for end-of-life vehicles, operated by Auto Recycling Nederland (ARN). The case studies described in Chapter 4, 5 and 6 all take place within the ARN network. A detailed description of the background and the setting is a prerequisite for full understanding of the case studies and the implications. Furthermore, Chapter 2 describes a typical case of a collective end-of-life product recycling system, operated by a central chain entity responsible for executing the EPR on behalf of the OEMs. The scope of generalization of the results of the thesis is limited to systems similar to ARN.

Chapter 3

Chapter 3 deals with the logistics concept, a hierarchical structure consisting of the supply chain strategy, the network structure and planning, control and information technology. We distinguish six typical determinants influencing the design of the logistics concept:

- Business strategy
- Existing forward supply chain
- Legislation and social pressure
- Supply characteristics
- Demand characteristics
- Product characteristics

Most of the literature takes these determinants as the starting point for the network design. The strategy element is often omitted. Chapter 3 first discusses the determination of the reverse supply chain strategy. After reviewing the literature on frameworks, we conclude that while the current literature is valuable, it misses an important dimension. We combine the approaches of Blackburn et al. (2004) and

Krikke et al. (2004b), which results in the two dimensional framework shown in Table 8.1.

Table 8.1. The time-value framework for reverse supply chain strategy.

		Value of returned product	
		Negative (negative externalities)	Positive (intrinsic value)
Time-dependency	Low (stable value)	*Control chain*	*Efficient chain*
	High (rapidly diminishing value)	*Protection chain*	*Responsive chain*

Our starting point is that all determinants are captured by the reverse supply chain strategy and the logical next step is to design the reverse supply chain network based on the chosen strategy; this is formalized in a proposition. Based on an extensive literature review, we summarize the network typologies developed for each type of return. The typologies are valuable for selecting a conceptual network model, but fail to provide explicit design principles: within a certain network typology, one can set multiple reverse supply chain strategies and vice versa. We must therefore conclude that some of the typical reverse supply chain determinants directly interfere with network design, bypassing the reverse supply chain strategy.

Beside the conceptual discussion, we also consider the modeling aspects in reverse supply chains, with a focus on network design. In Chapter 3 we extended the supply chain planning matrix of Meyr et al. (2002) to reverse supply chains. This matrix classifies supply chain planning processes in two directions: the planning scope and the nature of the process. This reverse supply chain planning matrix maps our discussion on network design. Network design is a strategic planning process, covering the entire chain: from acquisition, collection, grading and disposition, to recovery and finally distribution and sales of the returns.

In a review of the literature on the modeling of reverse supply chain network design we classified over 20 papers, describing the application of a network design model in a case study to design a reverse supply chain. Location-allocation models using mixed-integer linear programming dominate the field. The application of stochastic models is limited, although uncertainty is often denoted as specific for reverse supply chains. Most authors suffice with sensitivity analysis. In our opinion, special approaches dealing with stochastic elements are valuable for both forward and reverse supply chains in order to cope with demand and supply uncertainty. After all we state, based on the literature review, that the differences in modeling between forward and reverse supply chains seem limited and concern adaptations to fit the specific case. Adaptations are common to fit the real-life situation and this is not typical for reverse supply chains. In a proposition we state that the special reverse supply chain determinants do not justify the development of new models and algorithms for reverse supply chain network design. Model developments in forward and reverse supply chains should join forces.

The interaction of routing aspects in network design has received remarkably limited attention in the literature. Location-allocation models assume that the transportation cost parameters are known beforehand, and mostly base the parameters on linehaul distances. In this thesis we interpret network design to be broader than location-allocation models and also consider chain orchestration decisions, for example in routing and inventory management. Especially in reverse supply chains with low valued returns, transportation costs are a significant factor deserving special attention. The interaction of routing with network design is expected to result in significant cost savings even in forward supply chain applications as illustrated in the factory gate pricing example of Le Blanc et al. (2004b). This aspect is emphasized in a proposition at the end of Chapter 3, stating that network design should deal integrally with the logistics concept. More specific, network design exceeds location-allocation decisions and should interact with the lower level elements of the logistics concept, e.g. routing.

Chapter 4

Chapter 4 describes the case study involving a redesign of the network for LPG-tank recycling. From a reactive on-call collection system, the system is modified to a periodic collection system. The system has to change in order to raise the number of LPG-tanks handed in for degassing before being traded for reuse. The trade of non-degassed LPG-tanks worries ARN as the organization responsible for the execution of the EPR on end-of-life vehicles in the Netherlands.

A key issue in the analysis is the number of points at which the LPG-tanks should be collected. In a central strategy, a degassing plant is established, while in the regional strategy a mobile degassing facility periodically visits the consolidation centers of LPG-tanks for degassing. In the case study, we also analyze the effects of the period length and the size of the storage racks (carriers) of LPG-tanks.

Our methodology for analysis consists of two steps. First, we use a vehicle routing model to assess the effects of different lengths of the collection period and the size of the storage racks. Second, we use a location-allocation model to determine the optimal strategy: central or regional. Step 1 provides detailed transportation cost estimations for the model in step 2.

All things considered, ARN chose the central strategy with a 4 weekly collection system for large ELV-dismantlers and 8 weekly for smaller ELV-dismantlers, all using storage racks with a capacity of 12 LPG-tanks. Although the new periodic system is more expensive than the old on-call system, this is justified by the higher number of degassed LPG-tanks and the strengthening of the control of ARN.

Chapter 5

Chapter 5 of the thesis discusses a case in the collection of oil and coolant. The installation of new drainage equipment at the ELV-dismantlers, together with large storage tanks equipped with electronic metering, has created opportunities to watch inventory levels at a distance (telemetry). We study a change in the network, where the logistics service provider (LSP) is made responsible for timely emptying of the storage vessels. The change of responsibility reflects a change in chain orchestration. Since the telemetry allows foreseeing the occurrence of transportation orders weeks ahead, better planning opportunities occur for the LSP. The system is simulated over multiple years to analyze the long-run behavior. In each planning period we solve a route planning problem using a combination of route generation and route selection by solving a set partitioning problem.

Increasing the information availability in the chain enables the change of orchestration in combination with a forward-looking strategy. This results in cost savings of 18.9 %.

Chapter 6

Chapter 6 describes a case study in which advanced planning concepts in the container network of ARN are evaluated. We analyze the change of fixed assignment of ELV-dismantlers to LSPs, based on provincial boundaries, to an optimally fixed assignment and to a dynamic assignment. The latter implies setting up a chain conductor, collecting all the transportation orders and assigning them in routes to the LSPs. We also analyze the effects of bypassing the consolidation depot and transporting directly to the recyclers, and the effects of harmonizing the lifting mechanisms for containers.

To analyze the effects of the various options in the long-run, we adopt a simulation approach with periodically scheduled transportation orders. The transportation orders are scheduled using an algorithm based on generation of candidate routes based on neighborhoods structures, and selection of routes by solving a set partitioning problem.

In the analysis we show that the cost savings of loosening the restrictions on provincial boundaries together with optimizing the fixed assignments are approximately equal to the savings possible by adopting a dynamic assignment strategy, while they are much easier to achieve. In combination with allowing direct shipment to recyclers and standardizing the lifting mechanisms for containers, savings up to 19.2% are possible.

Chapter 7

In Chapter 7, the propositions formulated in Chapter 3, based on the literature, are validated and refined based on the case experience. Furthermore, we add new theory to explain the relation between reverse supply chain strategy and reverse supply chain network design. Chapter 7 describes the reflective cycle of our research methodology. Note that the formulated propositions are validated only in the domain defined, for which the organization in the case studies is a representative example in terms of Yin (2003). We now briefly discuss the three propositions.

Proposition 1: strategy and the relation with network design

The formulated strategy framework is a clear structure for determining the reverse supply chain strategy. Strategy is the starting point for design of the other elements of the logistics concept. However, we experience difficulties in translating the strategy directly to the network design. We therefore introduce the theory of the disposer decoupling point (DDP). The DDP is the point in the chain where the decisions on the recovery option, location, timing and volume of recovery are taken and separates the return-driven part (downstream) from the value-driven part (upstream) of the reverse supply chain. The positioning of the DDP in the chain is influenced along two dimensions. The first dimension is time-criticality, the degree to which time is an issue in obtaining control over the return, to maximize value recovery or to minimize negative externalities. The second dimension is the availability of information, which influences disposition decisions. These two dimensions are reflected in the determinants of supply, demand and product characteristics.
To summarize, we repeat the revised and definitive version of proposition 1:

Proposition 1 revised
The closed-loop supply chain strategy can be based entirely on the value of the returned product and the time-dependency of that value. The matching reverse supply chain strategy is either efficient, responsive, control or protection focused. Next to the strategy, so-called direct determinants are the basis for network design. The relationship with network design must be worked out using decoupling point theory.

Proposition 2: network design should be based on the logistics concept integrally

In proposition 1 we already indicate that network design is based on the strategy. Network design not only includes decisions on the location of facilities and the allocation of customers or disposers to the facilities, i.e. location-allocation, but also other aspects such as chain orchestration. Network design should therefore interact with all of the other elements of the logistics concept, especially in the planning, control and information technology. In the case studies, we find that routing decisions, in particular, interact with the network design. In the typical situation we consider, end-of-life recycling networks managed by a central chain entity that outsources the processes, transportation costs are an important factor and need to be considered in the reverse supply chain network design. In the three cases we show the importance of routing decisions. Omitting the routing component in the cases would make careful analysis impossible. This interaction is emphasized in the formulation of the revised proposition 2:

Proposition 2 revised
A reverse supply chain should deal integrally with the full logistics concept; the current reverse supply chain design literature is too much concerned with its single elements. Reverse network design exceeds location - allocation and should be based on the reverse supply chain strategy and interact with the lower level elements of the logistics concept. This requires combinations of models, e.g. location-routing and inventory routing models.

Proposition 3: the operations research consequences for network design

The special determinants of reverse supply chains are often used to justify the development of new operations research models and algorithms. In this thesis, we consider only models on network design. Our case experience indicates that although adaptations to the models are required, development of new algorithms is not justified. We suffice with the application of standard techniques. The modeling phase is adapted into two directions. First, we use a combination of models to address fully the questions posed; this is a direct result of proposition 2. Second, we alter the available models to cope with the situation at hand.
Comparing the models in the literature that describe situations similar to the case studies, we denote certain similarities, but the differences are too large for direct application. In cases where the development of special models is required, it seems worth considering whether the characteristics are typically “reverse” or whether they have a “forward” counterpart. For instance, stochastic network design models have been proposed to cope with uncertainty in reverse supply chains. However, the same models are applicable in forward applications where uncertainty can also be an issue. Research in forward and reverse supply chain network design should join forces. First, to learn from each other since differences between forward and reverse supply chains are limited. Second, to draw attention to the holistic view of the reverse supply chain as a part of the closed-loop supply chain.

Our view on the operations research consequences for reverse supply chain network design is reflected in the revised proposition 3.

Proposition 3 revised
The specific determinants of reverse supply chains do not lead to special supply chain design problems from an operations research point of view. Therefore, the development of special operations research models and algorithms is not justified, although the modeling needs to be adapted.

8.2 Contributions

This section provides an overview of the contributions of our research. A distinction is made between scientific and practical contributions, since we aim to contribute to both fields. In our view, business economics and operations research are essentially design sciences that should aim at developing practical knowledge for practitioners in the field.

8.2.1 Scientific contributions

The scientific contributions of this thesis can best be summarized as follows:

- A structured analysis of the logistics concept for reverse supply chains is provided.
- A new value-time based framework for determining the reverse supply chain strategy is introduced.
- Decoupling point theory in reverse supply chains is developed.
- The interaction of network design with routing elements is analyzed.
- The operation research modeling and algorithmic consequences for reverse supply chain network design are analyzed.
- Three real-life cases studies provide relevant fact finding in practice, as well as a basis to validate and extend current theoretical insights.
- Combining a case study research methodology with operations research. The OR community often neglects cases. Case study research relies mostly on methods of statistical analysis, although OR has the flexibility to simulate different circumstances and assumptions.

8.2.2 Practical contributions

The practical contributions are summarized as follows:

- Contributing to closing the gap between scientific research and practice by bringing theory and practice together in a set of design principles of help for practitioners in the field.
- Significant cost reductions in the three real-life projects in the network of Auto Recycling Nederland.
- Three well-documented real-life case studies on reverse supply chain redesign serving as inspiration.

8.3 Recommendations for further research

Every research effort is limited in the degree to which the results are valid and can be generalized. Additional research is usually necessary for further validation and generalization. As a result of the methodology followed, the results in this thesis can be generalized only to a small area in the field of closed-loop supply chains. The scope of this thesis is restricted to returns:

- of durable products in the end-of-life phase,
- where material recycling is the foremost recovery option,
- managed in collective systems,
- driven by environmental legislation setting strict recycling targets (EPR).

Our discussion focused mainly on:

- The interaction of determinants and their influence on the logistics concept.
- The interaction between the elements of the logistics concept: strategy, network design and planning, control and information technology.
- The modeling consequences for reverse supply chain network design.

Some concepts introduced in this thesis are promising to be of value in other areas, and we therefore recommend further research to validate and possibly refine the theory in other domains, e.g. for other types of returns. In particular, we recommend further research on the following issues:

- Validation and generalization of the strategy framework based on the time and value dimension for other types of returns.
- Extension and refinement of the theory of the disposer decoupling point, connecting reverse supply chain strategy to network design.
- Validation and generalization of network design and the interaction with other elements of the logistics concept, especially with vehicle routing, for other types of returns.
- Generalization of our findings on the modeling and algorithmic consequences for the differences between forward and reverse supply chains to support the various planning processes in the (reverse) supply chain planning matrix.

The case study methodology is a good way of practicing research to develop, validate and refine new theory. However, we need to stress that a good research design is needed in order to allow for further generalization. Unfortunately, this is often forgotten in the reverse logistics literature. In our opinion, the application of case based methodologies will lead to more practically relevant theory and is therefore recommendable.

The field of closed-loop supply chain management is a relatively unexplored area, where a great deal of work has yet to be done. The alleged complexity of reverse supply chains compared to forward supply chains is mainly caused by the immaturity of the field. This explains the current focus of many reverse supply chains on closing the goods flows, while paying limited attention to closing the information and market flows. Only when the goods, information and market flows are all closed, we can fully exploit the potential and find solutions that are both economically and environmentally sound. The closing of loops should take place through business opportunities, since only then closed-loop supply chains are sustainable in the long-run.

References

ACEA (2004). ELV country report charts July 2004. http://www.acea.be (November 4, 2004).

Adenso-Diaz, B. (2004). Call for papers on reverse production systems for special issue in Omega.

Agarwal, Y., Mathur, K. and Salkin, H.M. (1989). A set-partitioning-based exact algorithm for the vehicle routing problem. *Networks* 19: 731-749.

Angelelli, E. and Speranza, M.G. (2002). The periodic vehicle routing problem with intermediate facilities. *European Journal of Operational Research* 137: 233-247.

Archetti, C. and Speranza, M.G. (2004). Vehicle routing in the 1-skip collection problem. *Journal of the Operational Research Society* 55: 717-727.

Arge Altauto (2002). Altautoverwertung Kritik an Fondslösungen. http://www.arge-altauto.de/fondskritik1.htm. (Februay 14, 2002).

Arntzen, B.C., Brown, G.G., Harrison, T.P. and Trafton, L.L. (1995). Global supply chain management at Digitial Equipment Corporation. *Interfaces* 25(1): 69-93.

Auto Recycling Nederland (2002). Environmental report 2001. Amsterdam, The Netherlands.

Auto Recycling Nederland (2003). Environmental report 2002. Amsterdam, The Netherlands.

Auto Recycling Nederland (2004). Environmental report 2003. Amsterdam, The Netherlands.

Auto Recycling Nederland (2005). Environmental report 2004. Amsterdam, The Netherlands.

Balas, E and Padberg, M.W. (1976). Set partitioning: a survey. *SIAM Review* 18: 710-760.

Barros, A.I., Dekker, R. and Scholten, V. (1998). A two-level network for recycling sand. *European Journal of Operational Research* 110: 199-214.

Beamon, B.M. and Fernandes, C. (2004). Supply chain network configuration for product recovery. *Production Planning & Control* 15(3): 270-281.

Bebelaar D., Dalmijn, W.L. and De Jong, T.P.R. (2004). Future developments in car recycling in the Netherlands. 4th International Automobile Recycling Congress, Geneve, Switzerland.

Bell, W.J., Dalberto, L.M., Fisher, M.L., Greenfield, A.J., Jaikumar, R., Kedia, P., Mack, R.G. and Prutzman, P.J. (1983). Improving the distribution of industrial gases with an on-line computerized routing and scheduling optimizer. *Interfaces* 13: 4-23.

Bellmann, K. and Khare, A. (1999). European response to issues in recycling car plastics. *Technovation* 19: 721-734.

Berger, T. and Debaillie, B. (1997). Vestiging van disassemblagecentra voor hergebruik ter aanvulling van het bestaand distributienetwerk. Master thesis, University of Leuven, Belgium.

Bertrand, J.W.M. and Fransoo, J.C. (2002). Operations management research methodologies using quantitative modeling. *International Journal of Operations & Production Management* 22(2): 241-264.

Besluit Beheer Autowrakken (2002). Staatsblad van het Koninkrijk der Nederlanden 2002: 259.

Beullens, P. (2001). *Location, process selection and vehicle routing models for reverse logistics*. Ph.D. thesis, Katholieke Universiteit Leuven, Belgium.

Beullens, P., Van Oudheusden, D. and Van Wassenhove, L.N. (2004). Collection and vehicle routing issues in reverse logistics. In Dekker, R., Fleischmann, M., Inderfurth, K. and Van Wassenhove, L.N. (eds) *Reverse logistics, quantitative models for closed-loop supply chains*. Springer Verlag, Berlin, Germany.

Bisschop, J., Roelofs, M. (2001). *AIMMS the language reference*. Paragon Decision Technology B.V., Haarlem, The Netherlands.

Blackburn, J.D., Guide Jr., V.D.R., Souza, G.C. and Van Wassenhove, L.N. (2004). Reverse supply chains for commercial returns. *California Management Review* 46(2): 6-22.

Bloemhof-Ruwaard, J.M. (1996). *Integration of operational research and environmental management*. Ph.D. thesis, Wageningen University, Wageningen,The Netherlands.

Bloemhof-Ruwaard, J.M., Salomon, M. and Van Wassenhove, L.N. (1996). The capacitated distribution and waste disposal problem. *European Journal of Operational Research* 88: 490-503.

Bloemhof-Ruwaard, J.M., Van Wassenhove, L.N., Gabel, H.L. and Weaver, P.M. (1996a). An environmental life cycle optimization model for the European pulp and paper industry. *Omega* 24(6): 615-629.

Bloemhof-Ruwaard, J.M., Fleischmann, M. and Van Nunen, J.A.E.E. (1999). Reviewing distribution issues in reverse logistics. In Speranza, M.G. and Stähly, P. (eds) *New trends in distribution logistics*. Lecture notes in economics and mathematical systems, Springer Verlag, Berlin, Germany.

Bodin, L., Golden, B., Assad, A. and Ball, M. (1983). Routing and scheduling of vehicles and crews: the state of the art. *Computers and Operations Research* 10: 63-211.

Bodin, L., Mingozzi, A. and Baldacci, R. (2000) The rollon-rolloff vehicle routing problem. *Transportation Science* 43(3): 271-288.

Bumstead, J. and Cannons, K. (2002). From 4PL to Managed Supply Chain Operations. *Logistics & Transport Focus* 4(4): 19-25.

Caldwell, B. (1999). Reverse logistics. *Information Week online*, April 1999. http://www.informationweek.com/729/logistics.htm. (February 2, 2005).

Callioni, G., De Montgros, X., Slagmulder, R. and Van Wassenhove, L.N. (2005). Inventory driven costs. *Harvard Business Review* 83(3): 135-141.

Campbell, A., Clarke, L. and Savelsbergh, M. (2002). Inventory Routing in Practice. In Toth, P. and Vigo, D. (eds) *The Vehicle Routing Problem.* SIAM monographs on discrete mathematics and applications, Philadelphia, USA.

Caruso, C., Colorni, A. and Paruccini, M. (1993). The regional urban solid waste management system: a modeling approach. *European Journal of Operational Research* 70: 16-30.

Clarke, G. and Wright, J.W. (1964). Scheduling of vehicles from a central depot to a number of delivery points. *Operations Research* 12: 568-581.

Corbett, C.J. and Kleindorfer, P.R. (2001a). Environmental management and operations, part 1: manufacturing and eco-logistics. *Production and Operations Management* 10(2).

Corbett, C.J. and Kleindorfer, P.R. (2001b). Environmental management and operations, part 2: integrating operations and environmental management systems. *Production and Operations Management* 10(3).

Cruijssen, F. and Salomon, M. (2004). Empirical study: Order sharing between transportation companies may result in cost reductions between 5 to 15 percent. CentER Discussion Paper 2004-80, Tilburg University, Tilburg, The Netherlands.

De Brito, M.P (2003). *Managing reverse logistics or reverse logistics management*. Ph.D. thesis, Erasmus University, Rotterdam, The Netherlands.

De Brito, M.P. and Dekker, R. (2004). A framework for reverse logistics. In Dekker, R., Fleischmann, M., Inderfurth, K. and Van Wassenhove, L.N. (eds) *Reverse logistics, quantitative models for closed-loop supply chains*. Springer Verlag, Berlin, Germany.

De Brito, M.P. and De Koster, M.B.M. (2004). Product and material returns: handling and warehouse issues. In Dekker, R., Fleischmann, M., Inderfurth, K. and Van Wassenhove, L.N. (eds) *Reverse logistics, quantitative models for closed-loop supply chains*. Springer Verlag, Berlin, Germany.

De Graaf, M.M. (1999). Reverse logistics in de automobilebranche. In Van Goor, A.R., Flapper, S.D.P. and Clement, C. (eds) *Reverse Logistics* B8210. Ten Hagen & Stam, Deventer, The Netherlands.

De Koster, M.B.M., Flapper, S.D.P., Krikke, H.R. and Vermeulen, W.S. (2005). Recovering end-of-life large white goods: the Dutch initiative. In Flapper, S.D.P., Van Nunen, J.A.E.E. and Van Wassenhove, L.N. (eds) *Managing closed-loop supply chains*. Springer Verlag, Berlin, Germany.

De Koster, M.B.M. and Zuidema, J.P. (2005). Commercial returns in a mail order company: the Wehkamp case. In Flapper, S.D.P., Van Nunen, J.A.E.E. and Van Wassenhove, L.N. (eds) *Managing closed-loop supply chains*. Springer Verlag, Berlin, Germany.

De Meulemeester, L., Laporte, G., Louveaux, F.V. and Semet, F. (1997). Optimal sequencing of skip collections and deliveries. *Journal of Operational Research Society* 48: 57-64.

Debo, L.G. and Van Wassenhove, L.N. (2005). Tire recovery: the RetreadCo case. In Flapper, S.D.P., Van Nunen, J.A.E.E. and Van Wassenhove, L.N. (eds) *Managing closed-loop supply chains*. Springer Verlag, Berlin, Germany.

Dekker, R., Fleischmann, M., Inderfurth K. and Van Wassenhove L.N. (eds) (2004). *Reverse logistics, quantitative models for closed-loop supply chains*. Springer Verlag, Berlin, Germany.

Dethloff, J. (2001). Vehicle routing and reverse logistics: the vehicle routing problem with simultaneous delivery and pick-up. *OR Spectrum* 23: 79-96.

Directive 1999/44/EC of the European Parliament and of the council of 25 May 1999 on certain aspects of the sale of consumer goods and associated guarantees. *Official Journal of the European Communities* L 171: 12-16.

Directive 2000/53/EC of the European Parliament and of the council of 18 September 2000 on end-of-life vehicles. *Official Journal of the European Communities* L 269: 34-42.

Directive 2000/96/EC of the European Parliament and of the council of 27 January 2003 on waste electrical and electronic equipment. *Official Journal of the European Communities* L 269: 34-42.

Directive 2002/95/EC of the European Parliament and of the council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment. *Official Journal of the European Communities* L 37: 19-23.

Disney, S.M., Potter, A.T. and Gardner, B.M. (2003). The impact of vendor managed inventory on transport operations. *Transportation Research Part E* 39: 363-380.

Dror, M. and Ball, M. (1987). Inventory/Routing: Reduction from an annual to a short-period problem. *Naval Research Logistics* 34: 891-905.

Dror, M. and Levy, L. (1986). A vehicle routing improvement algorithm comparison of a greedy and a matching implementation for inventory routing. *Computers & Operations Research* 13(1) 33-45.

Dror, M. and Trudeau, P. (1996). Cash flow optimization in delivery scheduling. *European Journal of Operational Research* 88: 504-515.

Dumas, Y. Desrosiers, J., Soumis, F. (1991). The pickup and delivery problem with time windows. *European Journal of Operational Research* 54: 7-22.

Dyckhoff, H., Lackes, R. and Reese, J. (eds) (2004). *Supply chain management and reverse logistics*. Springer Verlag, Berlin, Germany.

Dyckhoff, H. Souren, R. and Keilen J. (2004a). The expansion of supply chains to closed loop systems: a conceptual framework and the automotive industry's point of view. In Dyckhoff, H., Lackes, R. and Reese, J. (eds) *Supply chain management and reverse logistics*. Springer Verlag, Berlin, Germany.

Ealey, L.A. and Troyano-Bermúdez, L. (2000). The automotive industry: a 30,000-mile checkup. *McKinsey Quarterly* 2000(1): 72-79.

Eisenhardt, K.M. (1989). Building theories from case study research. *Academy of Management Review* 14(4): 532-550.

Etira (2004). European Toner and Inkjet Remanufacturers Association. http://www.etira.org. (November 12, 2004).

European Commission (2002). Commission decision of 30 October 2001 on the waste disposal system for car wrecks implemented by the Netherlands. *Official Journal of the European Communities* L 68: 18-30.

European Recycling Platform (2005). http://www.erp-recycling.org. (May 23, 2005).

Ferguson, N.S. (2002). *An information system for end of life product recovery*. Ph.D. thesis, National University of Ireland, Galway, Ireland.

Fisher, M.L. (1997). What is the right supply chain for your product? *Harvard Business Review* 75(2): 105-116.

Flapper, S.D.P., Fransoo, J.C., Broekmeulen, R.A.C.M. and Inderfurth, K. (2002). Planning and control of rework in the process industries: a review. *Production Planning & Control* 13(1): 26-34.

Flapper, S.D.P. and Spengler, T. (2004). Call for papers on product recovery for special issue in OR Spectrum.

Flapper, S.D.P., Van Nunen, J.A.E.E. and Van Wassenhove, L.N. (eds) (2004). *Managing closed-loop supply chains*. Springer Verlag, Berlin, Germany.

Fleischmann, B. (1993). Designing distribution systems with transport economies of scale. *European Journal of Operational Research* 70: 31-42.

Fleischmann, B., Meyr, H. and Wagner, M. (2002). Advanced planning. In Stadtler, H. and Kilger, C. (eds) *Supply chain management and advanced planning*. 2nd edition. Springer Verlag, Berlin, Germany.

Fleischmann, B. and Klose, A. (eds) (2005). *Distribution logistics: advanced solutions to practical problems*. Lecture notes in economics and mathematical systems, Springer Verlag, Berlin, Germany.

Fleischmann, M., Bloemhof-Ruwaard, J.M., Dekker, R., Van der Laan, E.A., Van Nunen, J.A.E.E. and Van Wassenhove, L.N. (1997). Quantitative models for reverse logistics: a review. *European Journal of Operational Research* 103: 1-17.

Fleischmann, M., Krikke, H.R. Dekker, R. and Flapper, S.D.P. (2000). A characterisation of logistics networks for product recovery. *Omega* 28: 653-666.

Fleischmann, M., Beullens, P., Bloemhof-Ruwaard, J.M. and Van Wassenhove, L.N. (2001). The impact of product recovery on logistics network design. *Production and Operations Management* 10(2): 156-173.

Fleischmann, M. (2001). *Quantitative models for reverse logistics*. Lecture Notes in Economics and Mathematical Systems 501. Springer Verlag, Berlin, Germany.

Fleischmann, M., Bloemhof-Ruwaard, J.M., Beullens, P. and Dekker, R. (2004). Reverse Logistics Network Design. In Dekker, R., Fleischmann, M., Inderfurth, K. and Van Wassenhove, L.N. (eds) *Reverse logistics, quantitative models for closed-loop supply chains*. Springer Verlag, Berlin, Germany.

Fleuren, H.A. (1988). *A computational study of the set partitioning approach for vehicle routing and scheduling problems*. Ph.D. thesis, University of Twente, Enschede, The Netherlands.

Fleuren, H.A. (2001). *Operations research in de praktijk: een ware odyssee*. Tilburg University Press, Tilburg, The Netherlands.

Geyer, R. and Jackson, T. (2004). Supply loops and their constraints: the industrial ecology of recycling and reuse. *California Management Review* 46(2): 55-73.

Geyer, R., Neeraj, K. and Van Wassenhove, L.N. (2005). Reverse logistics in an electronics company: the NEC-CI case. In Flapper, S.D.P., Van Nunen, J.A.E.E. and Van Wassenhove, L.N. (eds) *Managing closed-loop supply chains*. Springer Verlag, Berlin, Germany.

Geoffrion, A.M. and Powers, R.F. (1995). Twenty years of strategic distribution system design: an evolutionary perspective. *Interfaces* 25(5): 105-127.

Geoffrion, A.M. and Krishnan, R. (2001). Prospects for operations research in the e-business era. *Interfaces* 31(2): 6-36.

Goetschalckx, M. and Jacobs-Blecha, C. (1989). The vehicle routing problem with backhauls. *European Journal of Operational Research* 42: 39-51.

Goh, T.N. and Varaprasad, N. (1986). A statistical methodology for the analysis of the life cycle of reusable containers. *IIE Transactions* 18(1): 42-47.

Goodman, A. (2000). Implementing sustainability in service operations at Scandic hotels. *Interfaces* 30(3): 202-214.

Gottinger, H.W. (1988). A computational model for solid waste management with application. *European Journal of Operational Research* 35: 350-364.

Guide Jr., V.D.R., Kraus, M.E. and Srivastava, R. (1997). Scheduling policies for remanufacturing. *International Journal of Production Economics* 48: 187-204.

Guide Jr., V.D.R., Srivastava, R. and Spencer, M.S. (1997a). An evaluation of capacity planning techniques in remanufacturing environment. *International Journal of Production Research* 35(1): 67-82.

Guide Jr., V.D.R. and Jayaraman, V. (2000). Product acquisition management: current industry practice and a proposed framework. *International Journal of Production Research* 38(16): 3779-3800.

Guide Jr., V.D.R. and Van Wassenhove, L.N. (2002). Closed-loop supply chains. In Klose, A., Speranza M.G. and Van Wassenhove, L.N. (eds) *Quantitative approaches to distribution logistics and supply chain management*. Lecture notes in economics and mathematical systems, Springer Verlag, Berlin, Germany.

Guide Jr., V.D.R., Harrison, T.P. and Van Wassenhove L.N. (2003). The challenge of closed-loop supply chains. *Interfaces* 33(6): 3-6.

Guide Jr., V.D.R., Teunter, R.H. and Van Wassenhove L.N. (2003a). Matching demand and supply to maximize profits from remunfacturing. *Manufacturing & Service Operations Management* 5(4): 303-316.

Guide Jr., V.D.R. and Van Wassenhove, L.N. (eds) (2003). Closed-loop supply chains. *Interfaces* 33(6).

Guide Jr., V.D.R. and Van Wassenhove, L.N. (2003a). Business aspects of closed-loop supply chains. In Guide Jr., V.D.R. and Van Wassenhove, L.N. (eds) *Business Aspects of closed-loop supply chains*. Carnegie Mellon University Press, Pittsburgh.

Guide Jr., V.D.R. and Van Wassenhove L.N. (eds) (2004). Closed-loop supply chains. *California Management Review* 46(2).

Guide Jr., V.D.R. and Van Wassenhove L.N. (2004a). Call for papers on closed-loop supply chains for special issue in Production and Operations Management.

Gungor, A. and Gupta, S.M. (1999). Issues in environmental conscious manufacturing and product recovery: a survey. *Computers & Industrial Engineering* 36: 811-853.

Haasis H.D., Inderfurth, K. and Spengler, T. (eds) (2001). Operations research and environmental management. *OR Spectrum* 23(1).

Heertje, A. (1977). *Heer Bommel als theoretisch econoom.* De Bezige Bij, Amsterdam, The Netherlands.

Herer, Y. and Levy, R. (1997). The metered inventory routing problem, an integrative heuristic algorithm. *International Journal of Production Economics* 51: 69-81.

Hesse Owen, S. and Daskin, M.S. (1998). Strategic facility location: a review. *European Journal of Operational Research* 111: 423-447.

Hoekstra, S. and Romme, J. (eds) (1994). *Integral logistic structures: developing customer oriented goods flow*. McGraw-Hill, London.

Inderfurth, K., Flapper, S.D.P., Lambert, A.J.D., Pappis, C.P. and Voutsinas, T.G. (2004). Production planning for product recovery management. In Dekker, R., Fleischmann, M., Inderfurth, K. and Van Wassenhove, L.N. (eds) *Reverse logistics, quantitative models for closed-loop supply chains*. Springer Verlag, Berlin, Germany.

Informs (2004). Operations Research: the science of better. http://www.scienceofbetter.org. (December 20, 2004).

Jayaraman, V., Guide Jr., V.D.R. and Srivastava, R. (1999). A closed-loop logistics model for remanufacturing. *Journal of Operations Research Society* 50(5): 497-508.

Jayaraman, V. and Linton, J. (2004). Call for papers on supply chain management in a sustainable environment for special issue in Journal of Operations Management.

Kanari N., Pineau, J.-L. and Shallari, S. (2003). End-of-life vehicle recycling in the European Union. *Journal of Metals* 55(8): 15-19.

Kelle, P. and Silver, E.A. (1989). Forecasting the returns of reusable containers. *Journal of Operations Management* 8(1): 17-35.

Keys, P. (1991). *Operational research and systems, the systematic nature of operational research*. Plenum Press, New York.

Kilger, C. and Schneeweiss, L. (2002). Demand fulfillment and ATP. In Stadtler, H. and Kilger, C. (eds) *Supply chain management and advanced planning*. 2nd edition. Springer Verlag, Berlin, Germany.

Kizilaya, E. and Gupta, S.M. (1998). Material flow control and scheduling in a disassembly environment. *Computers and Industrial Engineering* 35(1): 93-96.

Klausner, M. Grimm, W.M. and Hendrickson, C. (1998). Reuse of electronic motors in consumer products. *Journal of Industrial Ecology* 2(2): 89-102.

Klausner, M. and Hendrickson, C.T. (2000). Reverse-logistics strategy for product take-back. *Interfaces* 30(3): 156-165.

Klose, A., Speranza M.G. and Van Wassenhove, L.N. (eds) (2002). *Quantitative approaches to distribution logistics and supply chain management*. Lecture notes in economics and mathematical systems, Springer Verlag, Berlin, Germany.

Klose, A. and Drexl, A. (2004). Facility location models for distribution system design. *European Journal of Operational Research* 162: 4-29.

Kokkinaki, A., Dekker, R., Van Nunen, J.A.E.E. and Pappis, C. (2000). An explorative study on electronic commerce for reverse logistics. *Supply Chain Forum* 1: 10-17.

Kokkinaki, A., Zuidwijk, R.A., Van Nunen, J.A.E.E. and Dekker, R. (2004). Information and communication technology enabling reverse logistics. In Dekker, R., Fleischmann, M., Inderfurth, K. and Van Wassenhove, L.N. (eds) *Reverse logistics, quantitative models for closed-loop supply chains*. Springer Verlag, Berlin, Germany.

Krikke, H.R. (1998). *Recovery strategies and reverse logistic network design*. Ph.D. thesis, University of Twente, Enschede, The Netherlands.

Krikke, H.R., Kooi, E.J. and Schuur, P.C. (1999). Network Design in Reverse Logistics: A Quantitative Model. In Speranza, M.G. and Staehly, P. (eds) *New trends in distribution logistics*. Lecture notes in economics and mathematical systems, Springer Verlag, Berlin, Germany.

Krikke, H.R., Van Harten, A. and Schuur, P.C. (1999a). Business case Océ, reverse logistic network re-design for copiers. *OR Spectrum* 21: 381-409.

Krikke, H.R., Van Harten, A. and Schuur, P.C. (1999b). Business case Roteb: recovery strategies for monitors. *Computers & Industrial Engineering* 36: 739-757.

Krikke, H.R., Pappis, C., Tsoulfas, G and Bloemhof-Ruwaard, J.M. (2002). Extended design principles for closed loop supply chains: optimizing economic, logistic and environmental performance. In Klose, A., Speranza, M.G. and Van Wassenhove, L.N. (eds) *Quantitative approaches to distribution logistics and supply chain management*. Lecture notes in economics and mathematical systems, Springer Verlag, Berlin, Germany.

Krikke, H.R., Bloemhof-Ruwaard, J.M. and Van Wassenhove L.N. (2003). Concurrent product and closed-loop supply chain design with an application to refrigerators. *International Journal of Production Research* 41(16): 3689-3719.

Krikke, H.R., Le Blanc, H.M. and Van de Velde, S.L. (2004). Product modularity and the design of closed-loop supply chains. *California Management Review* 46(2): 23-39.

Krikke, H.R., Le Blanc, H.M., Van de Velde, S.L. (2004a). The Impact of Product Life Cycle Management on Circular Supply Chains - and Reverse. *The Icfaian Journal of Management Research* 3(6): 7-31.

Krikke, H.R., Van Nunen, J.A.E.E., Zuidwijk, R.A. and Kuik R. (2004b). E-business and circular supply chains: increased business opportunities by IT-based customer oriented return-flow management. In Fleischmann, B. and Klose, A. (eds) *Distribution logistics: advanced solutions to practical problems*. Lecture notes in economics and mathematical systems, Springer Verlag, Berlin, Germany.

Kroon, L. and Vrijens, G. (1995). Returnable containers: an example of reverse logistics. *International Journal of Physical Distribution & Logistics Management* 25(2): 56-68.

Lambert, A.J.D. (2003). Disassembly sequencing: a survey. *International Journal of Production Research* 41(16): 3721-3759.

Lambert, D.M., Cooper, M.C. and Pagh J.D. (1998). Supply chain management: implementation issues and research opportunities. *International Journal of Logistics Management* 9(2): 1-19.

Lambert, D.M. and Cooper, M.C. (2000). Issues in supply chain management. *Industrial Marketing Management* 29: 65-83.

Laporte, G., Louveaux, F. and Mercure, H. (1989). Models and exact solutions for a class of stochastic location-routing problems. *European Journal of Operational Research* 39: 71-78.

Laporte, G., Gendreau, M., Potvin, J.Y. and Semet, F. (2000). Classical and modern heuristics for vehicle routing problem. *International Transactions in Operational Research* 7: 285-300

Larson, A.L., Olmsted Teisberg, E. and Johnson, R.R. (eds) (2000). Sustainable business. *Interfaces* 30(6).

Le Blanc, H.M., Fleuren, H.A. and H.R. Krikke (2004). Redesign of a recycling system for LPG-tanks. *OR Spectrum* 26: 283-304.

Le Blanc, H.M., Van Krieken, M.G.C., Fleuren, H.A. and Krikke, H.R. (2004a). Collector managed inventory, a proactive planning approach to the collection of liquids coming from ELVs. CentER discussion paper 2004-22, Tilburg University, Tilburg, The Netherlands.

Le Blanc, H.M., Cruijssen, F., Fleuren, H.A. and De Koster, M.B.M. (2004b). Factory Gate Pricing: an analysis of the Dutch retail distribution. CentER discussion paper 2004-35, Tilburg University, Tilburg, The Netherlands. (To appear in the European Journal of Operational Research).

Le Blanc, H.M., Van Krieken, M.G.C., Fleuren, H.A. and Krikke, H.R. (2004c). Advanced planning concepts in the closed-loop container network of ARN. CentER discussion paper 2004-103, Tilburg University, Tilburg, The Netherlands. (To appear in OR Spectrum).

Le Blanc, H.M., Schreurs, R.P., Fleuren, H.A. and Krikke, H.R. (2005). The value of information in a container collection system for end-of-life vehicles. In Fleuren, H.A., Den Hertog, D. and Kort P. (eds) *Operations Research Proceedings 2004*. Springer Verlag, Berlin, Germany.

Lee, H.L. and Tang, C.S. (1997). Modelling the costs and benefit of delayed product differentiation. *Management Science* 43(1): 40-43.

Lee, H.L. (2002). Aligning supply chain strategies with product uncertainties. *California Management Review* 44(3): 105-119.

Lin, C.K.Y., Chow, C.K. and Chen, A. (2002). A location-routing-loading problem for bill delivery services. *Computers & Industrial Engineering* 43: 5-25.

Listes, O. (2002). A decomposition approach to a stochastic model for supply and return network design. Econometric Institute Report EI 2002-43.

Listes, O. and Dekker, R. (2005). A stochastic approach to a case study for product recovery network design. *European Journal of Operational Research* 160: 268-287.

Louwers, D., Kip, B.J., Peters, E., Souren, F. and Flapper, S.D.P. (1999). A facility location allocation model for reusing carpet materials. *Computers & Industrial Engineering* 36: 855-869.

Marin, A. and Pelegrin, B. (1998). The return plant location problem: modeling and resolution. *European Journal of Operational Research* 104: 375-392.

Matthews, H.S. (2004). Thinking outside the box: designing a packaging take-back system. *California Management Review* 46(2): 105-119.

Mayers, K. (2001). *An investigation of the implications and effectiveness of producer responsibility for the disposal of WEEE*. Ph.D. thesis. Brunel University. Uxbridge, United Kingdom.

Meredith, J. (1998). Building operations management theory through case and field research. *Journal of Operations Management* 16: 441-454.

Meyr, H., Wagner, M. and Rohde, J. (2002). Structure of advanced planning systems. In Stadtler, H. and Kilger, C. (eds) *Supply chain management and advanced planning*. 2nd edition. Springer Verlag, Berlin, Germany.

Min, H., Jayaraman, V. and Srivastava, R. (1998). Combined location – routing problems: a sythesis and future research directions. *European Journal of Operational Research* 108: 1-15.

Min, H. and Zhou, G. (2002). Supply chain modeling: past, present and future. *Computers & Industrial Engineering* 43: 231-249.

Minner, S. and Lindner, G. (2004). Lotsizing decisions in product recovery management. In Dekker, R., Fleischmann, M., Inderfurth, K. and Van Wassenhove, L.N. (eds) *Reverse logistics, quantitative models for closed-loop supply chains*. Springer Verlag, Berlin, Germany.

Minter, A. (2004). A grinding hunger for scrap. *Far Eastern Economic Review* March 25: 26-29.

Mirvis, P. and Googins, B. (2004). The best of the good. *Harvard Business Review* 82(12): 20-21.

Moll, R. (2003). Ford Motor Company and the Firestone tyre recall. *Journal of Public Affairs* 3(3): 200-211.

Mostard, J. and Teunter, R. (2002). The newsboy problem with resalable returns. ERIM report ERS-2002-89-LIS, Erasmus University, Rotterdam, The Netherlands.

Nagel, C. and Meyer, P. (1999). Caught between ecology and economy: end-of-life aspects of environmentally conscious manufacturing. *Computers & Industrial Engineering* 36: 781-792.

Naylor, J.B., Naim, M.M. and Berry, D. (1999). Leagility: integrating the lean and agile manufacturing paradigms in the total supply chain. *International Journal of Production Economics* 62: 107-118.

NEA (2004). Kostencalculaties in het beroepsgoederenvervoer over de weg, prijspeil 1-1-2004. Rijswijk, The Netherlands.

Nijkerk, A.A. and Dalmijn, W.L. (1998). *Handbook of Recycling Techniques*. Nijkerk Consultancy, Den Haag, The Netherlands, 4th edition.

OECD (2001). Proceedings of OECD seminar on extended producer responsibility, 13-14 December 2001, Paris, France.

Olhager, J. (2003). Strategic positioning of the order penetration point. *International Journal of Production Economics* 85: 319-329.

Ong, H.L., Ang, B.W., Goh, T.N. and Deng, C.C. (1996). A model for vending machine services in the soft drink industry. *Asia-Pacific Journal of Operational Research* 13: 209-224.

Orsata, R.J., Den Hond, F. and Clegg, S.R. (2002). The political ecology of automobile recycling in Europe. *Ogranization Studies* 23(4): 639-665.

Ossenbruggen, P.J. and Ossenbruggen, P.C. (1992). SWAP: a computer package for solid waste management. *Computers, Environment and Urban Systems* 16: 83-100.

Pappis, C.P., Rachaniotis, N.P. and Tsoulfas, G.T. (2005). Recovery and reuse of maritime containers: the Blue Container Line case. In Flapper, S.D.P., Van Nunen, J.A.E.E. and Van Wassenhove, L.N. (eds) *Managing closed-loop supply chains*. Springer Verlag, Berlin, Germany.

Püchert, H., Spengler, T. and Rentz, O. (1996). Strategische Planning von Kreislaufwirtschafts- un Redistributionssystemen – am Fallbeispiel des Altautorecyclings. *Zeitschrift für Planung* 7: 27-44.

Pugh, M.P. (1993). The use of mathematical models in evaluating resource recovery options. *Resource, Conservation and Recycling* 8: 91-101.

Realff, M.J., Ammons, J.C. and Newton, D. (1999). Carpet recycling: determining the reverse production system design. *Journal of Polymer-Plastics Technology and Engineering* 38: 547-567.

Realff, M.J., Ammons, J.C. and Newton, D. (2004). Robust reverse production system design for carpet recycling. IIE Transactions 36(8): 767-776.

Recall Data (2004). Automobile recall information archive. http://www.recalldata.org. (November 17, 2004).

Reloop (2004). Reverse logistics chain optimization. http://www.kuleuven.ac.be/cib/industry/projkt03.htm. (November 2, 2004).

RevLog (2004). Revlog, the European working group on reverse logistics. http://www.fbk.eur.nl/OZ/REVLOG/Introduction.htm. (November 2, 2004).

Rogers, D.S. and Tibben-Lembke, R.S. (1998). *Going backwards: reverse logistics trends and practices*. Reverse Logistics Executive Council.

Rogers, D.S. and Tibben-Lembke, R.S. (2001). An examination of reverse logistics practices. *Journal of business logistics* 22(2): 129-148.

Sakkas, N. and Manios, T. (2003). End-of-life vehicle management in areas of low technology sophistication. A case study in Greece. *Business Strategy and the Environment* 12: 313-325.

Salhi, S. and Rand, G.K. (1989). The effect of ignoring routes when locating depots. *European Journal of Operational Research* 39: 150-156.

Sander, K., Schilling, S., Zangl, S. and Lohse J. (2002). Rules on compliance with article 7.2 of directive 2000/53/EC. Ökopol, Hamburg, Germany.

Schmidt, W-P., Dahlqvist, E., Finkbeiner, M. Krinke, S., Lazzari, S., Oschmann, D. Pichon, S. and Thiel, C. (2004). Life cycle assessment of leightweight and end-of-life scenarios for generic compact class passenger vehicles. *The International Journal of Life Cycle Assessment* 9(6): 405-416.

Schreurs, R.P. (2004). Voorspelbaarheid van de inzameling van materialen afkomstig van autowrakken en de impact op de distributieplanning. Master thesis, Tilburg University, Tilburg, The Netherlands.

Schultmann, F., Engels, B. and Rentz, O. (2003). Closed-loop supply chain for spent batteries. *Interfaces* 33(6): 57-71.

Schultmann, F., Zumkeller, M. and Rentz, O. (2004). Integrating spent products' material into supply chains: the recycling of end-of-life vehicles as an example. In Dyckhoff, H., Lackes, R. and Reese, J. (eds) *Supply chain management and reverse logistics*. Springer Verlag, Berlin, Germany.

Seitz, M.A., Disney, S.M. and Naim, M.M. (2003). Managing product recovery operations, the case of automotive engine remanufacturing. Proceedings of the EUROMA POMS Conference, Como Lake, Italy.

Seitz, M.A. and Peattie, K. (2004). Meeting the closed-loop challenge: the case of remanufacturing. *California Management Review* 46(2): 74-89.

Shapiro, J.F. (2001). Modeling and it perspective on supply chain integration. *Informations Systems Frontiers* 3(4): 455-464.

Shih, L-H. (2001). Reverse logistics system planning for recycling electrical appliances and computers in Taiwan. *Resources, Conservation and Recycling* 32: 55-72.

Silver, E.A., Pyke, D.F. and Peterson, R. (1998). *Inventory management and production planning and scheduling*. John Wiley & Sons, New York, USA.

Spengler, T,. Püchert, H., Penkuhn, T. and Rentz, O. (1997). Environmental integrated production and recycling management. *European Journal of Operational Research* 97: 308-326.

Spengler, T., Ploog, M. and Schröter, M. (2003). Integrated planning of acquisition, disassembly and bulk recycling: a case study on electronics scrap recovery. *OR Spectrum* 25: 413-442.

Spengler, T. and Schröter, M. (2003). Strategic management of spare parts. *Interfaces* 33(6): 7-17.

Stadtler, H. and Kilger, C. (2002) *Supply chain management and advanced planning*. 2nd edition. Springer Verlag, Berlin, Germany.

Stiba (2004). Groene reparatie; de groene polis. http://www.stiba.nl/groene/introductie.htm. (October 22, 2004).

Stock, J., Speh, T. and Shear, H. (2002). Many happy (product) returns. *Harvard Business Review* 80(7): 16-17.

Teixeira, J., Antunes, A.P. and De Sousa, J.P. (2004). Recyclable waste collection planning - a case study. *European Journal of Operational Research* 158: 543-554.

Thierry, M.C., Salomon, M., Van Nunen, J.A.E.E. and Van Wassenhove, L.N. (1995). Strategic issues in product recovery management. *California Management Review* 37(2): 114-135.

Thierry, M.C. (1997). An analysis of the impact of product recovery management on manufacturing companies. Ph.D. thesis, Erasmus University, Rotterdam, The Netherlands.

Tibben-Lembke, R.S. and Rogers D.S. (2003). Retail reverse logistics in practice. In Guide Jr., V.D.R. and Van Wassenhove, L.N. (eds) *Business Aspects of closed-loop supply chains*. Carnegie Mellon University Press, Pittsburgh, USA.

Tibben-Lembke, R.S. (2004). Strategic use of the secondary market for retail consumer goods. *California Management Review* 46(2): 90-104.

Toffel, M.W. (2003). The growing strategic importance of end-of-life product management. *California Management Review* 45(3): 102-129.

Toffel, M.W. (2004). Strategic management of product recovery. *California Management Review* 46(2): 120-141.

Toktay, L.B., Wein, L.M. and Zenios, S.A. (2000). Inventory management of remanufacturable products. *Management Science* 46(11): 1412-1426.

Toktay, L.B. (2003). Forecasting product returns. In Guide Jr., V.D.R. and Van Wassenhove, L.N. (eds) *Business Aspects of closed-loop supply chains*. Carnegie Mellon University Press, Pittsburgh, USA.

Toktay, L.B., Van der Laan, E.A. and De Brito, M.P. (2004). Managing product returns: the role of forecasting. In Dekker, R., Fleischmann, M., Inderfurth, K. and

Van Wassenhove, L.N. (eds) *Reverse logistics, quantitative models for closed-loop supply chains*. Springer Verlag, Berlin, Germany.

Toth, P. and Vigo, D. (2002). *The vehicle routing problem*. Society for Industrial and Applied Mathematics. SIAM monographs on discrete mathematics and applications

Transumo (2004). Transumo project plan: betere mobiliteit voor morgen en 2010. Connekt, Delft, The Netherlands.

Van Aken, J.E. (1994). De bedrijfskunde als ontwerpwetenschap. *Bedrijfskunde* 66(1): 16-24.

Van Aken, J.E. (2004). Management research based on the paradigm of the design sciences: the Quest for Field-Tested and grounded technological rules. *Journal of Management Studies* 41(2): 219-246.

Van Breedam, A. (2001). Comparing descent heuristics and metaheuristics for the vehicle routing problem. *Computers & Operations Research* 28: 289-315.

Van Breedam, A. (2002). A parametric analysis of heuristics for the vehicle routing problem with side-constraints. *European Journal of Operational Research* 137: 348-370.

Van der Laan, E.A. (1997). *The effects of remanufacturing on inventory control*. Ph.D. thesis, Erasmus University, Rotterdam, The Netherlands.

Van der Laan, E.A., Salomon, M., Dekker, R. and Van Wassenhove, L.N. (1999). Inventory control in hybrid systems with remanufacturing. *Management Science* 45(5): 733-747.

Van der Laan, E.A., Kiesmüller, G., Kuik, R., Vlachos, D. and Dekker, R. (2004). Stochastic inventory control for product recovery management. In Dekker, R., Fleischmann, M., Inderfurth, K. and Van Wassenhove, L.N. (eds) *Reverse logistics, quantitative models for closed-loop supply chains*. Springer Verlag, Berlin, Germany.

Van Goor, A.R., Ploos van Amstel, M.J., Ploos van Amstel, W. (1998). *Fysieke distributie*. Stenfert Kroese, Houten, The Netherlands.

Van Hillegersberg, J., Zuidwijk, R.A., Van Nunen, J.A.E.E. and Van Eijk, D. (2001). Supporting return flows in the supply chain. *Communications of ACM* 44(6): 74-79.

Van Krieken, M.G.C., Fleuren, H.A. and Peeters, M.J.P. (2003). Problem reduction in set partitioning problems. CentER Discussion Paper 2003-80, Tilburg University, Tilburg, The Netherlands.

Van Krieken, M.G.C., Fleuren, H.A. and Peeters, M.J.P. (2004). A Lagrangean relaxation based algorithm for solving set partitioning problems. CentER Discussion Paper 2004-44, Tilburg University, Tilburg, The Netherlands.

Van Nunen, J.A.E.E. and Zuidwijk, R.A. (2004). E-enabled closed-loop supply chains. *California Management Review* 46(2): 40-54.

VDA (2003). Verband der Automobilindustrie, annual report 2003. Frankfurt/Main, Germany.

Veenstra, A.W. (2005). Empty container reposition: the port of Rotterdam case. In Flapper, S.D.P., Van Nunen, J.A.E.E. and Van Wassenhove, L.N. (eds) *Managing closed-loop supply chains*. Springer Verlag, Berlin, Germany.

Vidal, C.J. and Goetschalckx, M. (1997). Strategic production-distribution models: a critical review with emphasis on global supply chain models. *European Journal of Operational Research* 98: 1-18.

Vidal, C.J. and Goetschalckx, M. (2001). A global supply chain model with transfer pricing and transportation cost allocation. *European Journal of Operational Research* 129: 134-158.

Voss, C., Tsikriktsis, N. and Frohlich, M. (2002). Case research in operations management. *International Journal of Operations & Production Management* 22(2): 195-219.

Voutsinas, T.G. and Pappis, C.P. (2002). Scheduling jobs with values exponentially deteriorating. *International Journal of Production Economics* 79: 163-169.

VROM (2004). Landelijk afval beheerplan 2002-2012, deel 1 beleidskader, versie april 2004. Ministerie van VROM, Den Haag, The Netherlands.

Wagner, M. (2002). Demand planning. In Stadtler, H. and Kilger, C. (eds) *Supply chain management and advanced planning*. 2nd edition. Springer Verlag, Berlin, Germany.

Westkämper, E. and Van de Osten-Sacken, D. (1999). Methods and tools of life cycle management, optimizing the performance of manufacturing systems. In Jeswiet, D., Moore, T.N. and Oosthuizen, P.H. (eds) *Proceedings 6th international seminar on life cycle engineering*. Queen’s University, Kingston, Canada.

White, A.L., Stoughton, M. and Feng, L. (1999). Servicizing: the quite transition to extended producer responsibility. Tellus Institute, Boston, MA, USA.

White, C.D., Masanet, E., Rosen, C.M. and Beckman, S.L. (2003). Product recovery with some byte: an overview of management challenges and environmental consequences in reverse manufacturing for the computer industry. *Journal of Cleaner Production* 11: 445-458.

Yin, R.K. (2003). *Case study research: design and methods*. 3rd edition. Sage Publications, Thousand Oaks, CA, USA.

Zhang, Y. and Gershenson, J.K. (2003). An initial study of direct relationships between life-cycle modularity and life-cycle costing. *Concurrent Engineering* 11(2): 121-128.

Samenvatting

Achtergrond onderzoek

Closed-loop supply chains zijn de uitbereiding van de voorwaartse logistieke keten met een retourketen en overspannen daarmee de gehele productlevenscyclus “van wieg tot graf”. De motivatie van deze uitbreiding is gelegen in:

- de schaarste en toegenomen vraag naar natuurlijke grondstoffen,
- de trend naar product gebaseerde dienstverlening (o.a. leasing),
- de toegenomen fabrikantenaansprakelijkheid voor producten.

In dit proefschrift worden ontwerpcriteria ontwikkeld voor retourketens van producten aan het eind van hun levenscyclus, waarbij recycling wordt gedreven door producentenverantwoordelijkheid. De aandacht binnen deze ketens was in het verleden te veel gericht op het voldoen aan de wetgeving en te weinig op oplossingen die zowel economisch als milieutechnisch rendabel zijn. Als een representatieve case studie gebruiken we Auto Recycling Nederland (ARN). Deze organisatie is opgericht door de vertegenwoordigers van de autoindustrie en is belast met het voldoen aan de wetgeving voor afgedankte auto’s. De ontwerpcriteria voor retourketens zijn gebaseerd op literatuurstudie en worden op basis van de ARN cases gevalideerd en waar nodig aangescherpt. Een uitgebreide methodologie is opgesteld teneinde vanuit de literatuur en de cases tot generieke proposities te komen.

Afbakening onderzoek

Als gevolg van de gekozen methodologie, gebruik makend van praktijkcases in een bepaald gebied, kunnen de resultaten in dit proefschrift slechts beperkt worden gegeneraliseerd. De analyse richt zich op retouren:

- van duurzame producten aan het einde van hun levenscyclus,
- met materiaalrecycling als belangrijkste verwerkingsoptie,
- in collectieve systemen,
- die gedreven worden door milieuwetgeving op basis van producenten-verantwoordelijkheid.

Binnen dit gebied richt ons onderzoek zich met name op:

- De interactie tussen en de invloed van de typische retourlogistieke factoren op het integraal logistiek concept.

- De interactie tussen de verschillende onderdelen van het logistieke concept: logistieke strategie, netwerkontwerp en het besturingssysteem.
- De consequenties voor de OR modellering van het retourlogistieke netwerkontwerp.

Praktijk cases

In dit proefschrift worden drie praktijk cases beschrijven, die zich allen afspelen in het ARN netwerk.

LPG-tank case

De LPG-tank case gaat over het ontwerp van het logistieke netwerk voor de ontgassing van LPG-tanks. In een nieuw op te zetten systeem worden LPG-tanks periodiek ingezameld voor ontgassing. Het doel is om het inleverrendement te verhogen en de handel in niet ontgaste LPG-tanks tegen te gaan.
In de case is onderzocht waar de ontgassing plaats moet vinden: centraal, bij een vaste ontgassingsfabriek of regionaal, op een aantal depots die periodiek door een mobiele ontgassingsinstallatie worden bezocht. Goede transportkostenschattingen zijn in deze analyse essentieel, aangezien ook de optimale emballagegrootte en de lengte van de periode geanalyseerd dienen te worden. Het ontwikkelde model bestaat uit twee delen: een voertuigroutering model, dat een gedetailleerde transportkostenschatting maakt en een locatie-allocatie model, dat op basis van de geschatte transportkosten de optimale locaties bepaalt. Uiteindelijk is gekozen voor de centrale ontgassing met een inzamelfrequentie van 4 weken voor grote en 8 weken voor kleine autodemontagebedrijven. Het inleverrendement van LPG-tanks is gestegen van 54% naar 80%.

Olie en koelvloeistoffen case

De olie en koelvloeistoffen case beschouwt het proactief plannen van de inzameling van vloeistoffen in het ARN netwerk. Doordat autodemontagebedrijven uitgerust zijn met nieuwe aftapinstallaties met grote opslagtanks met elektronische volumemeting (telemetrie), is er op centraal niveau informatie beschikbaar over de voorraadniveaus. In de analyse beschouwen we een regieverschuiving in het netwerk, waarbij de logistieke dienstverlener verantwoordelijk wordt gemaakt voor het tijdig legen van de opslagtanks bij de autodemontagebedrijven. Door de informatie komende van de telemetrie, kan de logistieke dienstverlener de toekomstige behoefte aan inzameling van de autodemontage bedrijven inschatten en deze informatie gebruiken voor een efficiëntere planning.
Door het simuleren van het systeem over meerdere jaren is het lange termijn gedrag geanalyseerd. In elke planningsperiode is een routeplanningsprobleem opgelost door een combinatie van route generatie en het kiezen van een route schema door het

oplossen van een set partitioning probleem. Deze geschatte kostenbesparing van het nieuwe systeem is gelijk aan 19%.

Container case

De container case beschrijft de analyse van enkele planningsvarianten in het containernetwerk van ARN. Logistieke dienstverleners en recyclingbedrijven zijn op basis van provinciegrenzen toegewezen aan de autodemontagebedrijven. In de analyse beschouwen we het loslaten van de provinciegrenzen op twee manieren: op basis van een vaste toewijzing aan het dichtstbijzijnde depot en op basis van centraal plannen waarin een ketenregisseur dynamisch bepaald welke logistieke dienstverlener welk autodemontagebedrijf bezoekt. Daarnaast zijn de besparingen onderzocht van het standaardiseren van het takelmechanisme voor containers en het eventueel rechtsreeks afvoeren van containers naar het recyclingbedrijf zonder op- en overslag op het depot.
Om de lange termijn effecten van deze veranderingen te analyseren is gebruik gemaakt van simulatie, waarbij in elke planningsperiode een transportplan berekend wordt. Uit de analyse blijkt dat de dynamische toewijzing van logistieke dienstverleners nauwelijks beter presteert dan de optimale vaste toewijzing, terwijl deze veel eenvoudiger toe te passen is. Samen met het toestaan van rechtstreeks leveren en het standaardiseren van het takelmechanisme, zijn er besparingen tot 19% mogelijk.

Het integraal logistiek concept en de typische retourlogistieke factoren

Als leidraad voor de ontwikkeling van ontwerpcriteria maken we gebruik van het integraal logistieke concept, opgebouwd uit strategie, netwerk structuur en de logistieke besturing. Hierbij is het uitgangspunt dat een set van typische factoren hiërarchisch het ontwerp van het logistiek concept bepalen. De volgende “typische“ factoren worden beschouwd:

- Bedrijfsstrategie
- Bestaande voorwaartse logistieke keten
- Wetgeving en maatschappelijke druk tot recycling
- Aanbodkarakteristieken
- Vraagkarakteristieken
- Productkarakteristieken

Strategie voor retourketens

In de literatuur worden bovengenoemde factoren vaak direct in verband gebracht met het retourlogistieke netwerkontwerp, zonder expliciet de retourlogistieke strategie te beschouwen. In dit proefschrift doen we dit wel. Op basis van literatuuronderzoek hebben we een raamwerk ontwikkeld, dat op basis van de waarde van de retour en de tijdsafhankelijkheid van die waarde de retourlogistieke strategie bepaalt. De waarde dimensie kan zowel positief zijn door een economisch waarde of negatief door ongewenste neveneffecten. De tijdsafhankelijkheid verwijst naar de mate van verandering van de waarde over de tijd. Tabel 1 geeft het raamwerk weer.

Tabel 1. Raamwerk voor bepalen retourlogistieke strategie.

		Waarde retourproduct	
		Negatief	Positief
Tijdsafhankelijkheid	Laag (stabiele waarde)	*Control chain*	*Efficient chain*
	Hoog (snel afnemende waarde)	*Protection chain*	*Responsive chain*

Strategie en de relatie met netwerkontwerp

De logische volgende stap is om, op basis van de retourlogistieke strategie, het retournetwerk te ontwerpen. In de literatuur zijn verscheidene typologieën ontwikkeld voor het kiezen van een conceptueel model. Deze typologieën geven echter onvoldoende richtlijn voor netwerkontwerp. Binnen een conceptueel model kunnen namelijk meerdere logistieke strategieën gekozen worden, met andere woorden er kan geen eenduidige relatie tussen strategie en netwerkontwerp gelegd kan worden. Hiervoor hebben wij de ontkoppelpunt-theorie voor retourketens ontwikkeld. Het retour-ontkoppelpunt (DDP) is gedefinieerd als het punt in de keten waar de beslissingen over de wijze, het volume, de tijd en de locatie van verwerking van de retour worden genomen. Het DDP beïnvloedt het netwerkontwerp in twee richtingen:

- Tijdsafhankelijkheid van de waarde van de retour en het belang van het verkrijgen van controle over de retour in de keten.
- De mogelijke beschikbaarheid van informatie over de retour op dit punt.

Hoewel het DDP de relatie tussen strategie en netwerkontwerp verduidelijkt, is deze nog steeds niet eenduidig. De invloed van beschikbaarheid van informatie over de retour kan de positie van het DDP in beide richtingen beïnvloeden. Verder onderzoek naar de rol van ontkoppelpunten in retourketens is daarom van belang. Enkele van de typische factoren hebben wel direct invloed op het retourlogistieke netwerkontwerp, terwijl andere factoren indirect via de retourlogistieke strategie en het ontkoppelpunt, het netwerkontwerp beïnvloeden.

Netwerkontwerp en het integraal logistiek concept

Netwerkontwerp moet gebaseerd zijn op het integraal logistiek concept en is een wisselwerking met strategie en de logistieke besturing. Kenmerkend voor het type retouren dat beschouwd wordt in dit proefschrift, is de interactie tussen netwerkontwerp en voertuigplanning. Netwerkontwerp gaat verder dan locatie en allocatie beslissingen en omvat ook beslissingen omtrent de ketenregie. Met name bij laagwaardige producten, zoals in het geval van ARN, maken transportkosten een groot deel uit van de totale logistieke kosten. Uiteindelijk resulteert dat in het modelleren van de interactie van netwerkontwerp met andere elementen uit de logistieke besturing, zoals routering.

Modellering netwerkontwerp

De praktijkcases hebben aangetoond dat voor netwerkontwerp van retourketens de gebruikte algoritmen en modellen niet wezenlijk verschillen van de voorwaartse logistiek. Wel zijn er aanpassingen nodig, met name in de modellering van de problemen. Daar waar wel nieuwe modellen en algoritmen nodig zijn, zijn deze vermoedelijk niet specifiek voor retourlogistiek, maar net zo goed toepasbaar in de voorwaartse logistiek. Stochastische locatie-allocatie modellen, bijvoorbeeld, zijn zowel in de retourlogistiek (aanbodonzekerheid) als in de voorwaartse logistiek (vraagonzekerheid) van belang. Deze conclusie wordt ondersteund door de literatuur op het gebied van netwerkontwerp in retourketens, daar vaak wordt volstaan met aanpassingen van bestaande voorwaartse modellen. Onderzoekers zouden er in beide onderzoeksrichtingen goed aan doen de krachten te bundelen.

Contributies

De wetenschappelijke contributies van dit onderzoek kunnen als volgt worden samengevat:

- Een analyse van het integraal logistiek concept voor retourlogistieke ketens.
- Een nieuw raamwerk gebaseerd op waarde en tijd voor het bepalen van de retourlogistieke strategie.
- De toepassing van ontkoppelpunt-theorie in retourlogistieke ketens.
- Een analyse van de interactie tussen het retourlogistieke netwerkontwerp en voertuigroutering.
- Een analyse van de OR modelleringconsequenties voor netwerkontwerp in de retourlogistiek.
- Drie praktijk cases ter toetsing en ontwikkeling van de theorie teneinde nieuwe inzichten te verkrijgen.
- Het combineren van case studie onderzoek met operations research modellen.

De praktische contributies kunnen als volgt worden samengevat:

- Een bijdrage aan het dichten van de kloof tussen theorie en praktijk door het formuleren van ontwerpcriteria voor retourlogistieke netwerken.
- Drie praktijk cases resulterende in significante prestatieverbeteringen en inspiratie voor vergelijkbare toepassingen.

Aanbevelingen

De conclusies en concepten die gepresenteerd worden in dit proefschrift zijn mogelijk uit te breiden naar andere type retouren en andere retourketens. Hiervoor is meer onderzoek noodzakelijk. Met name de volgende kwesties dienen nader onderzocht te worden:

- Validatie en generalisatie van het raamwerk voor het bepalen van de strategie in een retourketen voor andere typen retouren.
- Uitbreiding en verfijning van de theorie over het retour-ontkoppelpunt, welke de verbinding vormt tussen de retourlogistieke strategie en het netwerkontwerp.
- Validatie en generalisatie van de interactie tussen netwerkontwerp en de andere onderdelen van het logistieke concept, zoals routering.
- Generalisatie van onze bevindingen op het gebied van de overeenkomsten en verschillen in modellen en algoritmen voor netwerkontwerp tussen retourketens en voorwaartse ketens.

Retourlogistiek is nog een relatief onontgonnen gebied, waar nog veel werk te doen is. De complexiteit wordt niet zo zeer veroorzaakt door de verschillen tussen voorwaartse en retourlogistiek, maar door de onvolwassenheid van het gebied. Voor de lange termijn is het van belang om zowel economisch als milieutechnisch efficiënte oplossingen te vinden. Dit kan alleen door het sluiten van materiaalstromen, informatiestromen en markten in de gecombineerde voorwaartse and retourlogistieke keten: closing loops in supply chain management.

About the author

Ieke (Henricus Maria) le Blanc was born on the 12th of April 12 1979 in Veghel. After completing grammar school (V.W.O) at the Zwijsen College in Veghel in 1997, he started studying Econometrics and Operations Research at Tilburg University. During the study he specialized in Quantitative Logistics. After writing his master thesis, he graduated cum laude in August 2001. His master thesis was based on an internship at Nokia Mobiles Phones in Bochum, Germany and dealt with demand-supply optimization. The thesis was awarded in 2002 with the thesis award of the Dutch Society for Statistics and Operations Research (VVS-OR).
After his study, he started as a PhD-student at Tilburg University in the Operations Research group of CentER Applied Research, where his research focused on the design of reverse supply chains. This research, in cooperation with Auto Recycling Nederland, resulted in a number of papers published in international journals and in this thesis. Beside his PhD research, he was involved in several applied research projects. As of October 2005, he works for TNT Express as network and infrastructure optimization officer.

Publications by the author in scientific journals

<u>Published</u>

Le Blanc, H.M., Fleuren, H.A. and Krikke, H.R. (2004). Redesign of a recycling system for LPG-tanks. *OR Spectrum* 26(2): 283-304.

Krikke, H.R., Le Blanc, H.M. and Van de Velde, S.L. (2004). Product modularity and the design of closed-loop supply chains. *California Management Review* 46(2): 23-39.

Krikke, H.R., Le Blanc, H.M. and Van de Velde, S.L. (2004). The Impact of Product Life Cycle Management on Circular Supply Chains - and Reverse. *The Icfaian Journal of Management Research* 3(6) 7-31.

Le Blanc, H.M., Schreurs, R.P., Fleuren, H.A. and Krikke, H.R. (2005). The value of information in a container collection system for end-of-life vehicles. In Fleuren, H.A., Den Hertog, D. and Kort P. (eds) *Operations Research Proceedings 2004*. Springer Verlag, Berlin, Germany.

<u>To appear</u>

Le Blanc, H.M., Van Krieken, M.G.C., Fleuren, H.A. and Krikke, H.R. Vehicle routing concepts in the closed-loop container network of ARN. To appear in *OR Spectrum*.

Le Blanc, H.M., Cruijssen, F., Fleuren, H.A. and De Koster, M.B.M. Factory Gate Pricing: an analysis of the Dutch retail distribution. To appear in *European Journal of Operational Research*.